Advanced Joining Technology

National Materials Advisory Board

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ADVANCED JOINING TECHNOLOGY

Report of the

Committee on Advanced Joining Technology

National Materials Advisory Board
Commission on Engineering and Technical Systems
National Research Council

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The report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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ABSTRACT

Joining procedures are used extensively in the manufacture of products important to the Department of Defense (e.g., armor, tanks, trucks, aircraft, microcircuits, and ships). Mechanical joining processes, fusion welding, resistance welding, and brazing are used widely. The relatively recent development of high energy-density joining techniques, both electron and laser beam, has broadened the scope of joining. Emerging materials, processes, and design technologies are expected to stimulate increased use of these and other sophisticated techniques.

In some instances, joining procedures have been selected empirically with little regard for the relationships between the chemical, mechanical, and physical properties of the base and filler materials or the effect of heat transfer on fusion-zone and heat-affected-zone mechanical properties. This practice often leads to less than optimum results, and its use in new materials and design technologies will create greater problems. Proper use of metal technology and science should minimize these problems.

This report presents a review of the science of joining and the state of technology for joining similar and dissimilar metals to one another, ceramics to ceramics, and metals to ceramics. With respect to ceramics, mechanical joints and metallurgical bonds are considered. Important emerging technologies and advanced joining techniques are discussed, and some of the critical gaps in fundamental joining knowledge that limit progress are identified. Future research is recommended to form a basis for improved understanding of the joining process in all its many forms, and to develop new and improved joining methods to meet future design challenges. The metal-to-metal combinations will continue to be the major joining assembly concern of the Department of Defense as it is in industry.

PREFACE

The National Materials Advisory Board is a unit of the Commission on Engineering and Technical Systems of the National Research Council. Its general purpose is the advancement of materials science and engineering in the national interest. It fulfills that purpose by providing advice and assistance to government agencies and private organizations on matters of materials science and technology affecting the national interest, by focusing attention on the materials aspects of problems and opportunities, and by making appropriate recommendations for the solution of such problems and the exploitation of the opportunities.

Joining has long been significant in the design and manufacture of many products. The production of many items important to the Department of Defense--from aircraft to ships to trucks--involves extensive use of joining techniques. In the past, joining generally was accomplished using the common processes of arc and oxy-fuel fusion welding, resistance welding, brazing, soldering, and mechanical attachment. The development of electron beam and laser welding, along with the refinements of other processes, during the past two decades has provided improved joining capability for some applications. The emergence of new materials and structures for use in advanced Department of Defense applications will require more fundamental knowledge of the joining process and proper use of metal technology and science. One such application in which advanced superalloys as well as ceramic components are of great interest is the heat engine. It should be emphasized, however, that metal-to-metal combinations have been and will continue to be the Department of Defense's major joining assembly concern.

Under the sponsorship of the Department of Defense (DoD), the National Materials Advisory Board (NMAB) initiated a committee study of advanced joining technology in the spring of 1980. The specific purposes of the study were to:

1. Recommend directions for future research in the field of joining technology,

2. Form a basis for more fundamental understanding of joining processes to maximize use of metal and ceramic technology and science in the joining process, and

3. Support the development of improved joining methods--especially those applicable to metal-to-metal, metal-to-ceramic, and ceramic-to-ceramic interfaces.

The committee structured its study so that gaps in the basic understanding of joining that impede its usage would be identified. It should be recognized, however, that because of the breadth and complexity of the subject, there has not been complete committee concensus on the coverage selected. In this report several key areas were reviewed: the science of joining; the state of the art concerning the joining of similar and dissimilar materials; and the joining requirements of emerging materials, and structures. The materials considered were iron-, aluminum-, and titanium-base alloys; superalloys (both nickel and cobalt base); and ceramics. The detailed review of ceramic-to-ceramic and ceramic-to-metal joining emphasized the technology associated with the use of ceramics in heat engines since the DoD considers an understanding of bonding mechanisms and processes in this area to be of great importance to critical programs.

Metallurgical joining procedures used commonly in the past include various types of fusion welding, resistance welding, and brazing. It is anticipated that many new DoD products will involve technologies requiring advanced joining methods. This trend has been recognized in numerous past studies sponsored by the Department of Defense, the National Aeronautics and Space Administration, the U. S. Coast Guard, and others. Most of these studies, however, were dedicated to specific areas of application. For example, the U. S. Coast Guard has sponsored studies to identify steels offering improved weldability in ship construction, to develop methods for the nondestructive inspection of longitudinal stiffener butt welds in commercial vessels, and to assess fillet weld strength parameters for ship building. The Air Force has funded work on forming and joining of aluminum powder metal alloys, and the Army conducted a metals joining technology workshop. Given this situation, it was concluded that the broad study of advanced joining techniques described in this report would be beneficial.

Performance goals for new military equipment and the national need for energy-efficient devices require that the fundamentals of joining processes be well understood. For example, an increase in the rotor strength and stability of lightweight aircraft engines is directly related to the development of drum or integral rotors. The advantages of drum rotors over mechanically tied rotors include reduced weight, greater stability, and lower cost. Joining process selection for all drum-rotor material combinations is of vital concern. With respect to power plants, emphasis currently is placed on the use of ceramics in heat engines because engine efficiency improves significantly at higher temperatures and ceramics have very good high-temperature strength characteristics. Brittle-materials design is therefore receiving continuing attention. Ceramics for burner-can applications are of particular interest but new design concepts, including joining techniques, that utilize the high-temperature strength and oxidation resistance of ceramics while maximizing structural integrity are required. Of course, when joining brittle materials with mechanical fastening systems, interface conditions and contact loading are critical.

New aluminum, titanium, steel, and superalloy compositions also will require improved joining procedures. Many of these materials (iron-, nickel-, cobalt-, titanium- and aluminum-base) will utilize powder metallurgy processing and dispersion strengthening. Welding of oxide

dispersion strengthened (ODS) alloys now results in a large strength decrease in the weld zone because the dispersoid is agglomerated or lost during joining. It is possible that the dispersoid could be retained during a laser layering process and even put into solution in an amorphous layer for subsequent aging. Use of techniques in which the base metal is not melted, such as brazing, may often be suitable for joining ODS materials.

Advances in joining technology must reduce joining costs and improve quality. This may well be achieved by adoption of laser-beam, electron-beam, narrow-groove, and solid-state welding processes. Improved isothermal brazing processes may be needed for advanced joining applications. Automation to minimize labor costs and maximize productivity, uniformity, and quality will be of major interest. Progress in the development of ultrasonics, computer-assisted radiography, acoustic emission, eddy currents, and residual-stress measurement, combined with increasing confidence in predicting critical crack length with advanced methodology of elastic-plastic fracture mechanics, should substantially increase the ability to recognize a significant defect and reduce the cost of weld repair and lead to much higher standards for weldment properties.

This report constitutes the committee's findings. Several conclusions are drawn and specific recommendations for future work in joining research and development are made.

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CONCLUSIONS

State of the Art

Information is available for the successful welding of many steel, aluminum, titanium, and superalloy similar metal combinations. Problems persist, however, in welding specific alloys of these classes. Considerable scientific and engineering data essential for welding are lacking.

<u>Steel.</u> The degree of difficulty in welding carbon and low-alloy steels is related to carbon content (i.e., the higher the carbon content, the poorer the weldability). Welding of steels with more than 0.5 percent carbon generally is avoided. The weldability of chromium corrosion-resistant steels and nickel-chromium stainless steels is good, with the exception of high carbon, martensitic grades (e.g., AISI type 440). There is special interest in welding high-strength steels with yield strengths of 100,000 psi or greater.

The weldability of cast irons is poor with formation of brittle, crack-prone welds.

<u>Aluminum.</u> Low-strength aluminum alloys are readily weldable, but hot tearing and loss of heat-affected-zone (HAZ) strength and corrosion resistance due to precipitate coarsening could be problems in the welding of high-strength aluminum alloys. Porosity in aluminum weld metal is due to solution of monatomic hydrogen that later precipitates as diatomic hydrogen gas. Aluminum is readily brazed with commercially available filler metals and with well known processes when proper techniques are employed.

<u>Titanium.</u> Weldability of most titanium alloys is good, but because of detrimental reactions with oxygen, nitrogen and hydrogen, welding must be done with very restricted exposure to air and careful attention to joint surface cleanliness. High-strength titanium alloys such as Ti-6Al-6V-2Sn and Ti-7Al-4Mo are susceptible to fusion-zone cracks. The brazing of titanium is fairly well established but additional development efforts are needed. Silver or aluminum alloys appear to be more widely used than the brazing filler metals.

Superalloys. Iron-, cobalt-, and nickel-base superalloys, except those with high aluminum and titanium contents, are welded with little difficulty. Nickel-base superalloys that have a slow aging reaction (e.g., alloy 718) also are welded without problems. Most welding concern is focused on the high-strength gamma-prime strengthened nickel superalloys and high precipitation strengthening-element (aluminum and titanium) content. The strength of fusion welds in superalloys usually is lower than the strength of the base metal and this has a deleterious effect on long-term weld performance. Further, the ability to weld superalloys with matching or near-matching filler metals has been hampered by the lack of suitable compositions in fine-diameter wire as well as by the inherently limited usefulness of superalloy compositions as weld metal.

Superalloys generally are welded using inert-gas-shielded arc welding processes, particularly gas-tungsten-arc welding; however, use of high-energy-density processes (i.e., electron beam and laser beam) is increasing because of their low heat input requirements, exceptional cleanliness, and ability to join relatively thick sections without filler metal. The optimum heat treatment for a given superalloy is an important consideration. Both solution treating and overaging have been recommended as pre-welding heat treatments. Alloy-composition-based formulas which permit welding response to be predicted accurately, have not been developed for superalloys. Because of recent cobalt price and supply problems, an effort is being made to replace cobalt alloys with nickel alloys and to reduce the cobalt content of nickel alloys. This could result in some welding problems since welding is usually a minor consideration in superalloy formulation and modified alloys with minimized cobalt content may be more difficult to weld.

Ceramics. In heat engine applications, ceramics must interface with themselves and with metallic structures. The state of the art of joining is immature and details are not available from any one source. The use of the mechanical attachment for ceramic-to-metal bonding is favored for heat-engine designs, and the metal-to-ceramic and ceramic-to-ceramic interfaces are of special concern due to high contact stresses and localized bonding. In mechanically attached ceramic-to-ceramic and ceramic-to-metal joints in turbine engine components, some form of compliant layer and/or lubricant is needed between mating members. Incomplete characterization of many ceramics (oxides, nitrides, carbides) has limited basic understanding of the nonmechanical joining of ceramics. Lack of information about silicon nitride microstructure, for example, prevents optimum joining material selection. Joining of reaction-bonded silicon nitride to itself and to hot-pressed silicon nitride has been accomplished in an argon atmosphere using a silicon slurry before nitriding. Solid-state brazing of silicon nitride using ZrO_2, Al_2O_3-SiO_2 powders, and Zr foil fillers has been done. Suitable joining of silicon carbide to itself has been accomplished by hot pressing, silicon brazing, germanium brazing, and glass sealing.

New Alloy Classes. Four classes of emerging high-temperature metals being developed as alternatives to standard superalloys are oxide-dispersion-strengthened (ODS) alloys (both iron- and nickel-base) including mechanically alloyed (MA) products, rapid-solidification-rate (RSR) nickel and aluminum powder alloys, directionally solidified nickel-base eutectics, and single-crystal gamma-prime-strengthened nickel superalloys. The latter two are being developed almost exclusively for turbine blades in aircraft turbine engines where welding is not required, whereas the other two are being considered for a variety of applications. Development of satisfactory joining procedures is essential for broad application of these materials. The joining of such alloys, whatever the base metal, is complicated because these materials derive their strength from controlled microstructures that are disrupted by fusion joining processes. The high energy-density joining processes, both electron and laser beam, have shown potential for solving this problem. Brazing, diffusion-welding, and isothermal-solidification methods are particularly attractive for joining ODS and RSR powder alloys because no melting of the base metal occurs.

Specific Conclusions

Breadth of Disciplines. Welding encompasses many scientific disciplines and involves a complex interplay of numerous material state phenomena. Thorough understanding of the mechanisms involved in welding therefore requires the application of these disciplines including thermal and electrical sciences, mass transport, phase transformations, and metallurgy. Material science knowledge for homogeneous materials is reasonably well established, but much fundamental scientific information for heterogeneous material that constitutes weld metal and heat-affected zones of the alloys considered by this report, is lacking.

Productivity. Emphasis on minimizing costs by improving weld productivity and reducing the introduction of defects are factors leading to increased automation of welding processes.

Understanding Fluxes. Many weld processes depend on fluxes to protect the weld metal from the environment, to refine and alloy the weld metal, and to stabilize the arc. Future processes will need more specifically tailored fluxes. It is essential for the production of certain high-quality welds that a better understanding of the role of each constituent of fluxes be obtained in order to provide more consistent flux behavior in the welding process.

Brazing, Diffusion-Welding, and Isothermal-Solidification. These processes are attractive for joining superalloys and controlled microstructure alloys because they do not involve fusion of the base metal and, yet, can produce joints that may complement base-metal properties. Certain limitations, which involve common elements used in the joining alloy composition as temperature depressants in isothermal-solidification may form compounds resulting in areas of weakness or brittleness.

Limitations of High Energy Welding. The disadvantages of the high-energy-density processes are inflexibility of joint design, extremely high thermal gradients accompanying rapid heating and cooling, low energy efficiency and high capital cost of laser-beam welding, high capital cost, plus vacuum operation cost in electron-beam welding, and the tendency to produce fine-grained weld structures having inferior high-temperature creep resistance as compared to coarser grained welds.

Environmentally Assisted Cracking. Environmentally induced weld cracking (i.e., hydrogen and stress-corrosion cracking continues to be a problem with some materials. These failures result from a combination of material properties, environments, and residual stress conditions.

Influence of Gradients. Poor performance of welds between dissimilar metals is due to the large gradients of compositions, microstructure, and properties across this type of weld. The mismatch in thermal expansion may cause significant stresses at the weld. Elevated-temperature use of dissimilar-metal welds promotes atom diffusion across the weld with accompanying microstructure change and instability. Many detrimental corrosion effects in dissimilar-metal joining are due to the formation of galvanic cells that accelerate the corrosion rate of the most anodic material or phase in the weld area.

A significant role of the filler metal in dissimilar-metal welds is to accept dilution from the different base metals without creating a crack-sensitive structure. A successful joint results when the weld metal has a ductile and continuous matrix phase, with the resulting weld metal composition at least as strong as that of the weaker of the parent metals.

Difficult Joining Situations. Traditional welding and brazing techniques that require high-temperature melting and solidification are difficult to use in some applications such as joining of alloys that experience numerous phase transformations during welding, dissimilar-metal joints where large melting-point or thermal expansion coefficient differences exist, special maintenance welding in difficult positions and environments, and the joining of materials with controlled microstructures. Diffusion welding, silver solid-state welding, isothermal-solidification and the use of shape-memory alloys in joining currently are occasionally being applied for such situations.

Structures. A new structural concept in the design of advanced energy-efficient aircraft engines is the integral or drum rotor wherein the rotors are welded together rather than mechanically tied as in older engines. Because of the need to join relatively thick sections without filler metal, the high energy-density processes, in particular electron-beam welding, are of interest in the drum rotor design.

Ceramic-to-Metal Joining. Although ceramics lack toughness and ductility, interest in their use in heat engines has increased because of their desirable high-temperature strength and corrosion properties and because of growing concern about U. S. dependence on foreign sources for several strategic metals.

Ceramic-to-metal vacuum-tight seals now are used routinely for vacuum tube envelopes. Ceramic-to-metal seals also have been used successfully in high-temperature applications in vacuum or inert atmospheres, but oxidation-resistant ceramic-to-metal seals for operation above 1830°F (1000°C) have yet to be developed. High-temperature data on ceramic-to-metal seals are lacking.

Nondestructive Testing and Adaptive Control. The increasing capability of defect detection technology has caused problems concerning definition of acceptable joints. At the same time, improved nondestructive inspection techniques are leading to increased efficiency in welding operations and improved weld quality. During the past 20 years there has been an amazing growth in the overall use of sophisticated nondestructive testing methods. The effectiveness of x-rays, gamma-rays, ultrasonics, eddy currents, infrared radiation, thermal radiation, acoustic emission, and computers in adaptively controlling weld quality should be developed further. However, detection of small weld defects is only the first step. An acceptance decision based on whether such defects compromise the structural integrity of the weldment is needed.

Metal Cleaning. Fluoride-ion cleaning processes have been developed that provide significant improvement in the removal of tenacious oxides and, thus, lead to improved capability in the brazing, diffusion-welding, and isothermal-solidification joining and repair brazing of superalloys and stainless steels.

Welding Hazards. Fumes from joining processes (i.e., Pb, Zn, Cd, Ni and Cr from metal and F from flux) continue to be a health concern.

RECOMMENDATIONS

Welding Science and Technology. Maximum use should be made of existing knowledge in joining technology. A large body of scientific information, technical data and applied scientific and engineering knowledge pertinent to joining technology exists. Joining methods, procedures, and materials therefore do not generally need to be selected empirically. Basic information, however, concerning many welding processes particularly advanced techniques, is limited and the physical property data available for some engineering alloys are not sufficient to permit accurate heat-flow calculations. Weldment properties cannot be predicted in most cases from process, filler-metal and parent-metal data.

The following basic welding research needs apply to all the materials covered by this report unless otherwise stated.

Research should be continued to provide improved understanding of the various aspects of the joining processes with particular emphasis on topics such as:

- o metallurgical interactions
- o phase transformations
- o high temperature diffusion
- o galvanic corrosion effects
- o mismatch of physical and mechanical properties of filler and base metals
- o cleaning and joint preparation
- o diffusion and phase transformations
- o weld pool chemical reactions
- o heat generation and transport
- o stress analysis, defects, and fracture mechanics
- o fluxes and health hazards

Increased emphasis in welding research should be placed on the first step of the scientific method (i.e., making extensive observations of the entire process) rather than only focusing on a specific limiting behavior. Programs should be developed to transfer the results of these scientific studies to the welding engineering and design community. This is of basic importance because weld properties are related to composition and prior history that include material response to the thermal activity associated with welding. A fundamental understanding of the influence of the welding process on weld integrity requires complete description of the thermal conditions.

Selection of preheat, interpass and postheat temperatures based on heat-flow and phase-transformation analyses should be developed for welding iron, titanium, aluminum, nickel, and cobalt alloys.

Research should be continued to determine the influence of alloy additions on weld microstructures and properties. This should provide an understanding of the effect of minor elements, either intentionally added or present as impurities on the weldability of superalloy, steel, titanium, and aluminum systems. This research should be approached from the standpoint of maximum tolerable levels of impurities as well as minimum effective contents of grain-boundary active elements.

Research to further improve brazing, diffusion-welding, and isothermal-solidification joining techniques should be continued so that these processes can be used advantageously for the joining of emerging ODS and RSR powder alloy materials.

Joining Brittle Metals. Research activity should be increased in the area of welding high-strength and brittle iron-base alloys. There is special interest in welding high-strength steels with yield

strengths 100,000 psi or greater. Because it is theoretically possible to avoid continuous brittle carbides along the fusion line, improved welding processes for cast irons may be achievable.

Joining Aluminum. Increased research in aluminum joining including development of filler-metal compositions should be supported because of limited fundamental data in this area. The relationship of phases in the fusion-zone microstructure and the role of the thermal cycle regarding hot-tearing susceptibility should be determined. Development of aluminum filler metals should be directed toward elimination of hydrate formation to avoid hydrogen gas porosity. Mechanical and corrosion behavior data of as-welded and post-weld heat-treated aluminum welds also should be compiled to determine the need for post-weld heating. Advanced quantitative techniques to determine accurately the dimensions and morphology of specific defects and of advanced stress analysis techniques to determine the actual stress distributions in the weldments should be developed. Continued development of analytical and experimental methods in fracture mechanics and improved understanding of the elastic-plastic behavior of weld metal is needed to design more closely to material mechanical capabilities.

Titanium Joining. The most important basic research needs for titanium welding are in areas of solidification and solid-state transformations. These studies should emphasize the dynamic conditions of the process and include correlation of weld-metal and HAZ microstructures with the welding process, determination of the effect of order-disorder phase reactions on mechanical properties, and investigation of thermal stability of weld phases.

Superalloy Cracking. An organized study of fusion zone and HAZ hot cracking should be undertaken to describe quantitatively the threshold strain, particularly for superalloys. Research to provide improved understanding of the microfissuring and strain-age cracking associated with superalloy welding should be continued so that methods to avoid their formation can be developed.

Prediction of Superalloy Welding Response. Work should be done to develop a chemistry-based formula that will permit accurate prediction of the welding response of the superalloys based on composition. Research in this area should be aimed at improving the understanding of solutioning, rate of precipitation, hot ductility, and rate of strength recovery on cooling.

Strategic Elements. The impact on weldability of changes in strategic metal contents in various alloys should be studied. One area of importance is establishment of the precise role of cobalt on superalloy weldability.

High Energy-Density Joining. Study of the high energy-density joining processes, particularly electron-beam and laser-beam welding,

should be continued. This research should be directed at assessing the trade-off between the low heat input and the high thermal gradient of these processes.

Precleaning. Study of pre-joining cleaning should be continued. This research should be aimed at developing improved techniques for use with steels, aluminum alloys, titanium alloys, superalloys, and new ODS and RSR powder alloys.

Automation. Continued development of automation in welding should be done to minimize labor and material costs and increase productivity. Automation also should be examined especially in the area of metal conservation as a means of reducing weldment defects that result in scrap losses or costly repairs.

Joining Dissimilar Metals. Metallurgical joining of materials with significantly different melting characteristics or thermal expansion coefficients should be avoided as much as possible; in such instances, mechanical fastening with proper design accommodations should be considered. Similarly, combinations of base metals and filler metals that produce excessively brittle weld areas generally should not be used. Where welding of such combinations is essential, development of special joining processes to handle these conditions is encouraged.

Fatigue of Weld Joints. Research in heterogeneous materials should be continued to explain fatigue crack propagation through multipass weld metal and the high-temperature service degradation of HAZ mechanical properties.

Hydrogen Susceptibility. Work should be done on testing methodology for hydrogen susceptibility so that weld service behavior may be accurately predicted. Improved techniques also are needed for determination of hydrogen in weld consumables and in weldments.

Health Protection. Programs should be undertaken, particularly related to the emission of toxic fumes, to guarantee the long-term health and safety of those in the welding environment.

Carbides and Nitrides. Model carbide and nitride systems should be synthesized to further the understanding of joining processes (e.g., ranging from the use of single crystals of silicon carbide and silicon nitride to precisely tailored compositions of each body with known grain boundary compositions and crystal sizes).

Data on Carbides and Nitrides. The collection of physical property data on carbide and nitride ceramic materials should be continued. Microstructural characterization should receive more emphasis since this property is important in developing an understanding of the joining process whether it be true chemical bonding or simply mechanical joining.

There is a need to collect, organize, and analyze all the available data on carbide and nitride joining methods in one report and to develop a basic understanding of the processes involved, whether they be mechanical joints or metallurgically bonded interfaces. The suitability of the various joining techniques by application, temperature, environment, etc., should be listed.

Joining Ceramics. Bonding technologies involved in the joining of existing and emerging heat engine ceramics, other than silicon carbide and silicon nitride, should be investigated. This research should include low thermal conduction applications where silicon carbide and silicon nitride components would be at a disadvantage.

Design of Ceramic-to-Metal Joints. Ceramic-to-metal joint design should be carried out using finite element fracture mechanics analysis techniques. Specific joining problems, or at least classes of problems, should be addressed. Recommended projects are the development of joining methods for a ceramic piston cap to a metallic piston for the adiabiatic diesel and engine attachment of a ceramic rotor to a metallic shaft for the turbine engine.

Ceramic composites using either a glass matrix and fine SiC fibers or a ceramic matrix with dispersion of ceramic particles (particulate composite) offer long-range promise for heat engine applications because of their improved toughness. Research in the joining of these ceramic composites is needed since this area is as yet unexplored.

NDT of Ceramic-to-Metal Joints. Ceramic-to-metal joint test techniques, both nondestructive and destructive, that correlate with engine test results need to be developed to reduce expensive test rig and actual engine testing to a minimum.

Oxidation of Joints. Oxidation and corrosion studies of joints are needed for all types of ceramics including oxide, carbide, and nitride joints. Protective coatings over ceramic joint areas should be evaluated for oxidation resistance improvement.

Tribology studies of high temperature lubricants that can serve as barrier and compliant layers in mechanical ceramic joints should be conducted in simulated engine environments. Also studies are needed on sliding friction between mechanically mated ceramic-ceramic and ceramic-metal interfaces.

Chapter 2

LIMITATIONS OF KNOWLEDGE IN THE SCIENCE OF WELDING

Welding encompasses many scientific disciplines. It involves a complex interplay of numerous solid, liquid, gaseous, and plasma state phenomena that can be categorized as indicated in Table 1. Contributing to the complexity of welding processes is the fact that a large number of these phenomena take place simultaneously in relatively small volumes (0.1 to 10 mm^3), over short distances (1 to 20 mm), and frequently over short time periods of time (nonequilibrium).

TABLE 1 Scientific Disciplines Encompassed by Welding

Chemistry	Physics	Mechanics
Chemical reactions	Physical properties	Mechanical properties
Thermodynamics	Electrical properties	Statics
Kinetics	Plasmas	Dynamics
Electrochemistry	Heat and mass transport	Fracture mechanics
Alloy composition	Fluid flow	Residual stresses
Dilution	Heat flow	Distortion
Slag-metal reactions	Solid and liquid phase diffusion	Restraint
		Structural design, jigs, and fixtures
	Crystal (atomic) structure	
	Dislocations	
	Vacancies	
	Phase transformations	
	gas-liquid	
	liquid-solid	
	solid-solid	

Thorough understanding of the mechanisms involved in welding requires the application of these disciplines. However, it is necessary to develop programs that carefully transfer the results of scientific studies to the welding engineering and design community. Considerable research has been done to explain specific limiting behavior in the joining of materials. Very little has been devoted to the first scientific step (i.e., making

careful observations of the entire process). Compared to other sciences and technologies, there is limited fundamental welding research in the United States.

It is the purpose of this chapter to identify selected scientific knowledge limitations with respect to welding and to list research opportunities but not necessarily to set priorities relative thereto. The discussion is to focus on academic disciplines rather than on the weldability of specific materials or the various welding processes.

THERMAL SCIENCE

Welding processes generate thermal activity (Christensen and Davies 1965; Kou et al. 1981; Meyers et al. 1967; Rosenthal 1941; Rykalin 1974) and weld properties are directly related to material response to this thermal history. A basic understanding of the influence of the welding process on weld properties and integrity requires that the thermal conditions be described completely. This includes heat generation, melting and solidification, heat flow in the heat-affected zone (HAZ), fluid flow in the fusion zone (Milner and Woods 1971), metallurgical response to a given thermal procedure, and the influence of thermal expansion on residual stresses and distortion. A comprehensive effort involving heat-flow calculations instrumentation is needed to analyze the various thermal experiences.

The heat-transport process must be characterized fully (Frost et al. 1981; Jones et al. 1980) and this requires careful determination of the important physical and chemical variables involved (Schellhase 1979; Shaw 1975) and their interrelationships. The role of heat-generation and heat-transport processes on the resulting weld-bead morphology also is of interest (Essers and Walter 1981; Mills 1979; and Schwemmer et al. 1979). Such research should be interdisciplinary and supported adequately over a sufficient period of time.

MECHANICS AND MECHANICAL METALLURGY

The mechanical integrity of welds is the basic concern of the engineer responsible for their performance in service. Welds may show a variety of discontinuities such as multiple phases, inclusions, porosity, steep property gradients and cracking. The increasing capability of detection technology has resulted in a major problem concerning the definition of an acceptable weld. Detection of small weld cracks requires an acceptance decision based on whether or not such defects compromise the structural integrity of the weldment. Research should be devoted to the development of advanced quantitative techniques to determine accurately the dimensions and morphology of specific discontinuities and defects, and to development of advanced stress analysis techniques to determine the actual stress distributions in the weldments of a specific joint geometry and location.

The stress analysis must consider both the structural loading and the residual stress due to thermal expansion and shrinkage. Both of these topics must be studied to provide reliable information for advanced fracture mechanics analysis (American Welding Society 1981). Continued development of analytical and experimental methods in advanced fracture mechanics and of a better understanding of the elastic-plastic and fully plastic weldments behavior is essential if the economic advantages of designing more closely to the mechanical capabilities of materials are to be realized.

Weld microstructure and properties are heterogeneous. The HAZ shows steep gradients in microstructure and properties because each position in the HAZ is subjected to differing thermal, chemical, and mechanical experiences. The structure of the solidified weld fusion zone of alloys is both cored and segregated and, thus, is heterogeneous on both the macro- and micro-structural levels. Furthermore, multipass welding operations amplify the resulting heterogeneity of the weld by producing microstructures that cyclically vary from bead to bead. Material science has developed the essential principles to accommodate problems associated with phase transformations, mass transport, and mechanical metallurgy in homogeneous materials. An extension of these fundamentals to heterogeneous materials is required to improve knowledge of weld behavior. Explanations for fatigue crack propagation through multipass weld metal and the degradation of the mechanical properties of the HAZ of weldments in high-temperature service, for example, will require a better understanding of atomic processes in heterogeneous materials.

Environmentally induced cracking, such as hydrogen and stress corrosion cracking, continues to be a major problem associated with the welding of specific alloy systems (Coe 1973). Testing methodology for hydrogen susceptibility needs particular attention so that service behavior may be predicted accurately (Andersson 1979; Coe 1973; Tsunetomi and Murakami 1971). Better analytical chemistry techniques need to be developed to provide an accurate and rapid analysis of the hydrogen content of welding consumables and of weldments (Ball et al. 1981). Improved understanding of the stress-corrosion cracking behavior of weldments in a variety of industrial environments is of primary interest (Baeslack et al. 1979; Betz and Leung 1980; Viswanathan et al. 1979).

PHASE TRANSFORMATIONS

Phase transformation science is important in welding metallurgy, and weld microstructure may be the result of numerous phase transformations as influenced by thermal history. The complexity of predicting weld microstructures and properties is aggravated by multipass processes. The reactions involved may include solidification, segregation, constitutional undercooling, eutectoidal decomposition, athermal transformations, and precipitation.

New explanations of microstructural behavior in the solidification structure of austenitic weld metal (i.e., the quantity, morphology, and

distribution of delta ferrite) is a recent example of the application of phase transformation fundamentals (Hauser 1982; David 1981; David et al. 1979; Lippold and Savage 1979). The composition and properties of the fusion zone are related directly to the composition of the welding consumable, the base metals, and the welding process. Attractive fusion-zone properties have been obtained by proper alloying of the welding consumables. The specific role of microalloying, usually by residuals or contaminants, in the phase transformation of the fusion zone is important if the weld-metal properties are to be consistent with high-quality mill products. Oxygen, for example, has been found to influence the nature of the ferrite phase in mild-steel weldments (Abson et al. 1978; Cochrane and Kirkwood 1978; Eager 1978; North et al. 1978). It now is known that acicular ferrite which is promoted if the oxygen content of the weld metal is low, is essential for optimum toughness in steel welds. Interstitials also are known to influence the weld metal properties of titanium, aluminum, and stainless steels. Concepts of modification (change in morphology of microstructural constituents) have been demonstrated to apply in weld metal with relatively high cooling rates (Cross and Olson, 1981). Sodium has been found to modify aluminum-silicon weld microstructure by increasing the ductility of the alloy. Physical metallurgy research is needed to determine the influence of alloy additions (including microalloy additions, residual elements, and contaminant content) on weld microstructure and properties. Further, there is insufficient correlation of weld-metal microstructure to weld properties. Work in both areas should lead to more effective use of alloy additions in welding.

The extremely fast cooling rates experienced during welding require special efforts to extract meaningful phase transformation information. Only with comprehensive use of advanced analytical techniques (e.g., optical and electron microscopy combined with microstructural level chemical analysis) can the phase transformations of the weldment be analyzed, characterized, modeled, and controlled.

PYROMETALLURGY

Many welding processes depend on fluxes (Jackson 1973) to protect the weld metal from the environment, refine and alloy the weld metal, and stabilize the arc, and each welding process flux has specific requirements. For example, flux viscosity must be low enough to allow for effective flux-metal reactions and weld-pool gas removal but must be high enough to give sufficient environmental protection and weld-bead support.

Commercial welding fluxes are based on natural minerals and nearly all have residual elements that serve no design function. However, industrial experience indicates that, in some cases, these impure minerals are much more satisfactory flux ingredients than the chemically pure form of the primary compound in the mineral. It is essential for high-quality welds that a better understanding of the specific role of each component of the

flux be obtained. Better formulated and more consistent welding fluxes are needed for a variety of applications (e.g., submerged-arc welding of arctic line pipe, electroslag welding of thick-section alloy steels, and underwater welding).

Welding pyrometallurgical data in the literature are extremely limited. Basic research in welding fluxes requires first the preparation and study of a series of binary-, ternary-, and quaternary-component fluxes so that the role of each specific component can be studied, leading to modeling of the atomic processes involved. If simple model systems are found to be unsatisfactory, then systematic variation of a single compound's content in a series of fluxes could provide similar information.

Welding Fumes

Concern over welding fume hazards will promote major new research efforts by the welding consumable manufacturers (Delong 1978; Heile and Hill 1975; Silk 1974). Stainless steel welding processes may change drastically due to findings that hexavalent chromium is a potential carcinogen (Kimura et al. 1979; National Institute for Occupational Safety and Health 1976). Similarly the removal of copper coating, an element identified as a carcinogen, from steel welding wire has increased the welding wire's susceptibility to corrosion, hydrogen pickup, and the potential for arc instability. The Swedish welding consumable industry already is identifying the degree of health hazard (as indicated by a number on their electrodes) (Swedish Standard 1979) and U. S. industry should do the same if it intends to compete in the international marketplace.

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Chapter 3

THE JOINING OF SIMILAR METALS

This chapter comprises a brief summary of the status of weldability and brazability of each of the alloy classes considered in this report and the relevant joining processes.

STEELS AND CAST IRONS

Welding

The state of the art of welding steels is well established. The low-carbon, structural, low-alloy, ferritic and martensitic corrosion-resistant, and austenitic stainless steels are all readily welded by many processes.

The degree of difficulty in welding the carbon and the low-alloy steels (containing less than 5 percent total alloy content; Ni, Cr, Mo, V) is directly related to carbon content--the lower the carbon, the easier the welding. Welding of the medium- to high-carbon steels (above 0.5 percent C) generally is avoided. Stress-relief heat treatment after welding is recommended to temper any martensite formed in the weld or HAZ. Welding of the ferritic and martensitic chromium corrosion-resistant steels is generally accomplished quite readily. Stress-relief heat treatment should follow welding of these steels, particularly the air-hardening grades (e.g., AISI type 410), to temper the martensite formed in the weld and HAZ. Welding of the high-carbon martensitic corrosion-resistant steels (e.g., AISI type 440), containing about 1 percent carbon, is difficult and usually avoided. The weldability of the chromium-nickel austenitic stainless steel grades (e.g., AISI types 304, 316, 321, 347, and 310) is very good. If nonstabilized austenitic stainless steels with more than 0.03 percent C are welded (i.e., those not containing small amounts of titanium or columbium [niobium]), solution heat treatment and rapid cooling through the sensitization temperature range is required to restore maximum corrosion resistance in the weld and HAZ. The need for solution treatment is minimized for the low-carbon grades, 304L and 316L.

Some current steel welding projects include research which should continue in environmental cracking, the interaction of alloying elements including tramp elements relative to notch toughness, and ferrite vein cracking. There also is special interest in research in the

welding of the high-strength steels with yield strengths equal to or greater than 100,000 psi. These include HY130 and other quenched and tempered martensitic steels.

Welding of cast irons produces an excessively brittle, crack prone HAZ, and little success in welding these materials has been experienced. The inability to weld cast irons into complex assemblies with mechanical integrity limits their use. Because it is theoretically possible to avoid the formation of continuous brittle carbides along the fusion line with proper processing, an increase in research activity in this area would be worthwhile.

Brazing

Steels and cast irons are routinely joined by brazing using torch and furnace methods. Torch brazing is accomplished at 1000-1200^{o}F with silver brazing alloys. Furnace brazing generally is done at 1900-2000^{o}F using copper or nickel-boron alloys.

ALUMINUM WELDING

Recent aluminum welding development work has been conducted in support of industrial applications. For example, a high-deposition gas-metal-arc welding process was developed for fabricating thick-section aluminum pressure vessels for liquified natural gas storage. Another development is the partial-vacuum electron-beam welding of die-cast automotive engine alumium manifolds. Basic understanding of aluminum welding metallurgy is developing slowly because of the limited amount of fundamental research performed in this field. Further significant work is being done to develop filler-metal alloys.

A major problem in welding high-strength aluminum alloys is hot tearing of the fusion zone due to shrinkage stresses imposed during solidification. Although extensive weldability tests have been performed to characterize the relative hot-tearing susceptibility of various alloys, the results have been inconclusive in terms of defining the actual mechanism involved. Recent studies have shown that the presence of impurities (e.g., silicon and iron) can have a pronounced effect on hot-tearing susceptibility (Evancho 1980). The relationship of the type, amount, morphology, and distribution of phases in the fusion-zone microstructure to filler-alloy composition and hot-tearing susceptibility should be determined. The role of the thermal cycle in hot-tearing susceptibility also should be studied (Chihoski 1979).

Porosity that forms when monatomic hydrogen dissolves in the molten weld pool and later precipitates as diatomic hydrogen gas during solidification is another aluminum welding problem. Recent studies with aluminum-magnesium filler alloys have shown that the primary source of

hydrogen in the weld pool is a complex hydrate found on the outer surface of the filler wire (Martukanitz 1980). Future cladding of aluminum-magnesium filler wires with high-purity aluminum may resist hydrate formation and reduce porosity.

Significant loss in strength and corrosion resistance of heat-treated aluminum alloy welds can occur as a result of overaging (precipitate coarsening) in the HAZ. Transmission electron microscopy studies are being done to characterize HAZ microstructures. New wrought alloys with lower susceptibility to deleterious reactions due to welding and no need for post-weld heat treatment may be developed from these studies. More mechanical and corrosion behavior data of as-welded and post-weld heat-treated welds should be compiled to determine when post-weld heat treating is required.

Most aluminum brazing is successfully accomplished in vacuum furnaces, salt pots, or with hot air or gas atmospheres using fluxes. Braze sheets in which the brazing filler metal is pre-clad to the base metal are commercially available. Techniques encompassing fluxes, of which dip brazing is one, require careful and complete removal of the flux residue. Intricate or hollow brazements, in which the salt of flux is not completely removed, may corrode and fail, particularly if the components are thin-walled. Improved methods of flux removal are needed.

In vacuum brazing, the newest of the aluminum brazing techniques, flux is not needed. Therefore, this type of corrosion and failure is eliminated. For vacuum brazing, much effort has been applied to develop braze sheet with magnesium additions to the filler metal. Many of these braze sheets also have some magnesium in the base metal--usually a modified alloy of AA3003. In large components, such as heat exchangers, extended time at brazing temperature is necessary to obtain bonding of all joints. Further work is needed to determine the optimum compositions of filler metals and base metals to prevent problems due to diffusion of elements in the braze into thin-walled base metal.

Alloys that have a solidus above 1100^{o}F are easily brazed with binary aluminum-silicon filler metals.

TITANIUM ALLOYS

Welding

Present knowledge concerning titanium-base alloy weldability has been documented thoroughly (American Welding Society 1972; American Society for Metals 1980; Army Materials and Mechanics Research Center 1978; Battelle Columbus Laboratory 1972; Becker et al. 1980; Burns and Bangs 1977; Monroe and Mortland 1967; and Vagi et al. 1965). The high strength-to-density ratio of the titanium-base alloys has been instrumental in focusing fabrication efforts on thin-section aeronautical and aerospace applications

rather than on thick-section applications. In petrochemical applications, emphasis has been on the cladding of vessels and piping with as thin a layer of titanium as possible relative to acceptable corrosion resistance and cost effectiveness. Current efforts are directed toward the welding of thick-section titanium (greater than 3/8 in. thick). In contrast to the development of fabrication methods for high-strength steels for Navy and Air Force applications considerably fewer in-depth process and metallurgical titanium-alloy welding investigations have been conducted.

The weldability of the several classes (commercial purity, alpha, near alpha, alpha-beta, and beta alloys) of titanium alloys is well established. At high temperatures, oxygen, nitrogen, and hydrogen react with titanium and reduce its ductility and toughness markedly. Therefore, the principal welding precautions include thorough surface cleaning of the joint and adequate shielding from the interstitial elements by welding in the absence of air, usually in an argon atmosphere or a vacuum. The consumables that are used also must be clean.

The commercial-purity alloys are readily weldable using commercial-purity filler wire or autogeneous welding. Ti-8Al-1Mo-1V is the highest strength alpha alloy having good weldability.

Alpha-beta titanium alloys include Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-6Al-2Cb-1Ta-0.8Mo (Ti-100), Ti-7Al-4Mo, Ti-6Al-2Mo-4Zr-2Sn, Ti-5Mo-4.5Al-1.5Cr (Corona 5), and Ti-3Al-2.5Sn. Ti-6Al-4V is by far the most widely used titanium alloy. The heat-treating and welding of the alpha-beta alloys can have significant effects on mechanical properties, and weldability varies widely. For example, high-strength Ti-6Al-6V-2Sn and Ti-7Al-4Mo alloys are susceptible to fusion-zone cracking, but use of pure Ti filler metal minimizes cracking. Cooling weldments of Ti-6Al-2Cb-1Ta-0.8Mo or Ti-6Al-4V alloys through the ductility trough temperature range may cause weld cracking.

The metastable beta alloys characteristically have the highest ductility of the titanium alloys. They generally are welded easily in the solution-annealed condition and used in the as-welded condition. Post-weld heat treatment to increase strength is accompanied by a significant loss of ductility (American Welding Society 1972; American Society for Metals 1980; Becker and Baeslack 1980; Monroe and Mortland 1967; Rothman 1970; Vagi et al. 1965). Beta alloys include Ti-13V-11Cr-3Al, Ti-15V-3Cr-3Sn-3Al, Ti-8V-7Cr-4Sn-3Al-1Zr, and Ti-8V-4Cr-3Mo-2Fe-3Al.

The fusion-welding processes commonly used with titanium alloys are gas-tungsten-arc, gas-metal-arc, plasma-arc, and electron-beam welding which are performed in the absence of air to prevent interstitial element contamination. Arc-welding processes using fluxes for shielding from interstitial element contamination (shielded-metal-arc, flux-cored-arc, submerged-arc, and electroslag welding) are not used in the United States. Due to the unavailability of large quantities of high-purity argon gas in

the early 1960s (Mishler 1964), the Soviets began work on flux development for submerged-arc and electroslag welding of titanium alloys. Detailed reviews of the Soviet efforts have been published recently (Burns and Bangs 1977; Hallowell 1980).

The most important basic research needs appear to be in the areas of solidification and solid-state transformations under conditions representative of welding (Becker et al. 1980). An improved basic understanding of transformation behavior will contribute to an understanding of other basic phenomena associated with the welding of titanium alloys including as-welded strength, ductility, toughness, and corrosion resistance. Studies should emphasize dynamic behavior (heating and cooling rates and strain rate) from room temperature to temperatures approaching the melting point. Continuous cooling transformation diagrams should be developed for various alloys as functions of prior thermal and mechanical history, cooling rate, and strain rate. This research should include correlation of weld-metal and HAZ microstructures with welding processes and procedures including previously deposited weld metal, investigation of order-disorder phase reactions (e.g., Ti_3Al) and their effect on mechanical properties as functions of composition and prior thermal and mechanical history, and investigation of the thermal stability of phases occurring in titanium-alloy weldments.

Brazing

As is the case with the welding of titanium and its alloys, reaction with interstitial elements during brazing causes embrittlement (American Welding Society 1972, 1978; Howden and Monroe 1968; Pattee 1973). Reactions with oxygen and nitrogen form compounds that are stable over wide temperature ranges, and although such compounds passivate the metal surface and enhance the corrosion resistance of titanium in certain environments, their presence at the brazing temperature inhibits wetting of the base metal by the filler metal. Thus, for brazing, titanium surfaces must be cleaned carefully and protected from contamination by inert gases or vacuum. Use of fluxes for surface protection has been limited to low-temperature torch brazing (Pattee 1973).

Reactions between titanium and the filler metal during brazing depend on the mutual solubility of the two metals. Heating titanium to the beta-temperature range increases the solubility of most metals in the base metal and more reaction between the base metal and the filler metal can be expected. Brazing titanium at temperatures below the beta transus is, therefore, preferred. Brazing processes for titanium-base alloys include furnace, torch, and induction. These methods are discussed extensively in the literature (American Welding Society 1963, 1972, 1978; Howden and Monroe 1968; DeCecco and Parks 1953; Pattee 1973). Induction brazing provides a short brazing cycle that minimizes base-metal and filler-metal reactions. Furnace brazing using an inert gas atmosphere or a vacuum requires a longer cycle but accommodates large parts and complex joint

designs. Oxyacetylene torch brazing with special fluxes can be used by skilled personnel and short cycle times can be obtained. Dip brazing generally is not recommended due to possible titanium alloy contamination by the salt bath.

Selection of brazing cycles compatible with the heat treatment required for alpha-beta titanium alloys can be difficult. Ideally, brazing should be conducted 100 to 150°F (38-65°C) below the beta transus, but this can adversely affect tensile properties developed by prior heat treatment. With the beta alloys, the beta transus, of course, is not a problem, but too high a brazing temperature will cause ductility loss. Therefore it is best to heat treat the assembly after brazing, but unfortunately this practice often results in excessive distortion.

The commonly used filler metals for brazing titanium are divided into four main groups: silver-base alloys, titanium-base alloys, diffusion-brazing using electrodeposited-interlayer alloys, and aluminum-base alloys. Molten silver reacts with titanium to form intermetallic compounds. However, the compound TiAg that forms during brazing is reasonably ductile and does not cause an excessively brittle brazed joint (DeCecco and Parks 1953). Silver alloys have been the most widely recommended filler metals for brazing titanium even though the 1760°F (960°C) melting point of silver is high enough to require the heating of some of the alpha-beta alloys above their beta-transus temperatures (American Welding Society 1963; Meridith 1953; Tiner 1956). Use of up to 3 percent lithium as an alloy addition to silver reduces the melting temperature to 1450°F (790°C) so that brazing can be accomplished without alloying with the titanium-base metal. Silver-lithium alloys are susceptible to oxidation at 800°F (427°C) and show poor corrosion resistance to salt environments (Faulkner and Lewis 1960). Despite limited salt corrosion resistance, Ag-28Cu-0.2Li is another silver-lithium alloy found suitable for brazing titanium on the basis of heat-treatment requirements, strength, corrosion, and oxidation resistance (Rudy et al. 1959).

Silver-manganese alloys (up to 15 percent Mn) also have been used for titanium brazing (Clark 1959). These alloys are most suitable for applications where good strength at elevated temperatures is required. Their main disadvantage is their 1850°F (1010°C) melting temperature, which decreases brazing wettability (Vaccari 1965).

Silver-aluminum alloys also show promise as filler metals for brazing titanium. Ag-5Al and Ag-12.5Al, with brazing temperatures of 1600°F (870°C) and 1450°F (790°C), respectively, wet and flow on titanium with a minimum of alloying.

Development of silver-base brazing alloys for use at temperatures in the aging range of the heat-treatable titanium alloys 900 to 1100°F (480 to 590°C) has not been successful. Ag-24Cu-19Ge-1Ti, with a flow temperature of 1100°F (590°C), was tried but poor joint properties resulted. Other silver alloys containing copper and tin were found to produce brittle joints with mediocre shear strengths (Smeltzer et al. 1967.)

Early work on titanium-base alloys for brazing titanium was carried out by Long and Ruppender (1954). Two eutectic alloys, Ti-66Ni (melting point 2030°F or 1110°C) and Ti-28Ni (melting point 1750°F or 950°C) also have been used. Additions of copper and cobalt to replace some of the nickel were found to depress the melting point of the alloys still further. Flow temperatures in the range of 1700 to 1900°F (925 to 1040°C) and brazed-joint tensile shear strengths in the range of 37,000 to 48,000 psi were recorded.

Investigation has shown Ti-Zr alloys to be good for brazing titanium foils (Smeltzer et al. 1967). Ti-45Zr-5Al-4.75Be alloy was selected for brazing titanium honeycomb.

Electrodeposited copper has been used frequently for the diffusion brazing of titanium to itself or to other materials. Shinyaev and Bondarev (1966) diffusion brazed titanium metal and two alpha-beta alloys using deposited layers of Cu, Cu-Ni-Cu, and Cu-(Co-Ni)-Cu. Joint strengths approaching that of the base metal were obtained. Perun (1967) has reported that diffusion brazing using thin foil copper interlayers and suitable brazing conditions can produce joint strengths similar to that of Ti-6Al-4V base metal. When used as interface materials, titanium and zirconium were found to produce good joints in Ti-8Al-1Mo-1V alloy. Pure copper is considered to be a good interface material because it forms a transient, eutectic liquid phase with titanium, which enhances intimate contact and permits low pressures to be used for brazing. The eutectic liquid is removed by the diffusion of copper into the titanium, and solidification occurs at a constant temperature.

Bondarev et al., (1964) used electrodeposited layers of copper both to protect titanium from contamination and to reduce the amount of brittle intermetallic compound formed during the silver brazing of titanium alloys to copper, stainless steel, and heat-resisting steel. Strong joints (up to 50,000 psi) were obtained by careful control of the brazing parameters (i.e., temperature, time, and thicknesses of the electrodeposited layer of copper).

In the area of aluminum filler metals for brazing titanium, industry is using unalloyed aluminum (AA series 1100), Al-1.2Mn alloys (AA series 3003), and the normal Al-Si series of brazing filler metals. The choice of filler metal depends on the specific component requirements.

SUPERALLOYS

Superalloys are iron-, cobalt-, or nickel-base materials developed to provide high-temperature strength, creep resistance, and oxidation resistance at elevated temperatures. The single most important application for this class of materials is gas turbine engine components.

Welding

Since nickel-base materials are the most prominent of the superalloys, they will be emphasized in this chapter. Iron-base superalloys generally are used in less demanding applications and cobalt-base alloys are welded with little difficulty. Low-strength, solid-solution Ni-Cr-Fe and Ni-Cr-Mo alloys also are readily weldable. Most welding concern then is focused on the high-strength, gamma-prime strengthened nickel superalloys (those containing aluminum and titanium).

Weldability is a prime consideration in the selection of superalloys for some gas turbine and other high-temperature applications. For example, alloy 718 has a particularly slow aging reaction (Eiselstein 1963) that makes it a relatively weldable high-temperature nickel-base alloy. This material, therefore, is used widely in applications where welding is required. Cobalt-base alloys have been selected for large section and vane applications. Their good weldability is an important factor in the weld repair of castings and in overhaul repair of parts.

PROCESSES

Inert-Gas-Shielded Arc-Welding Processes

Most nickel-base and cobalt-base superalloys are joined by one or more of the inert-gas-shielded arc-welding processes. These processes include gas-metal-arc, plasma-transferred-arc, and gas-tungsten-arc welding. Although all three of the inert-gas-shielded welding processes are used with superalloys, gas-tungsten-arc (GTA) welding is predominant. Its primary advantages are extreme cleanliness and low heat input. In addition, the process is suitable for either manual or automatic operation.

Most GTA welding is performed using direct current with straight polarity (i.e., electrode is negative with respect to the workpiece). This results in most of the welding heat (approximately 70 percent) being directed into the workpiece. If an alternating current is used, only 50 percent of the arc heat is directed to the workpiece. This results in an effective lowering of heat input to the base metal and some marginal improvement, particularly in HAZ response. A modification of the GTA process that has received only little examination is the use of pulsed DC welding in which the GTA welding arc is switched between two current levels, a peak and background current. This has the advantage of lowering heat input while maintaining the penetration characteristics of the higher constant current weld. Research concerning the application of pulsed current GTA, particularly with improved feedback and computer control technology, could improve the GTA welding of superalloys.

Although plasma-transferred-arc (PTA) welding is used primarily in surfacing applications, it also has potential for improving the joining of superalloys (Kelley and Hughes 1971). The process is essentially GTA

welding but the arc between the tungsten electrode and the workpiece is modified by a plasma gas stream that is directed in a tight spiral in the immediate vicinity of the electrode. The effect of this plasma gas is to direct the arc downward and shape it, resulting in a stronger, more forceful arc that has a higher energy density than a gas tungsten welding arc and that can be operated at much greater arc lengths. Because of this difference in arc characteristics, it appears that some advantages in penetration and consistency in welding superalloys could be gained by using PTA as a substitute for GTA welding.

A modification of the PTA process allows the plasma-arc equipment to operate in a nontransferred-arc mode. This results in a welding arc from the plasma-arc torch that is analogous to an oxyacetylene flame or the arc in a plasma-spray coating device. It can produce extremely low heat input because there is no electrical connection between the arc and the workpiece. The welding current in the nontransferred-arc process generally does not exceed 30 amperes. The nontransferred-plasma-arc process has been used in some superalloy applications, particularly for small surface defect repair (Hauser 1968), but its use is limited by the inherent lack of arc force. The inability of the nontransferred-plasma-arc process to disrupt tenacious superalloy surface oxides is another limitation of the process.

High Energy-Density Welding Processes

The high energy-density welding processes, laser beam (LB) and electron beam (EB), are being applied increasingly in the joining of superalloys (Adams 1974). Their particular advantages include very low heat input into the workpiece, exceptional cleanliness, the ability to weld relatively thick sections without filler metal, use of a simple square butt joint design, and high finishing rate. The disadvantages of these processes are the relative inflexibility of joint design and the extremely high thermal gradients that accompany the rapid heating and cooling. The need to operate EB welding in a vacuum can be a cost disadvantage. No protective atmosphere is required for LB welding, but argon shielding often is used. A limitation of LB welding is its extremely low energy efficiency, which results both from the inefficient conversion of input electrical energy to output laser-beam energy and from losses in the interaction between the laser beam and the metals being joined. Because metals reflect light and because laser energy is simply a coherent form of light energy, there is a problem in promoting interaction of the laser beam with the material to be processed. Once fusion is achieved, the transfer of laser energy to the workpiece becomes much more efficient.

The trade-off between low heat input and high thermal gradient is an important factor in the application of these high energy-density processes to superalloy joining. Relatively little research has been performed on the use of preheat to reduce stresses occurring across the weldment on cooling after fusion. There are obvious engineering problems that must be solved in order to use extremely high preheats and/or slow cooling rates with these processes. Because the high energy-density processes are

mechanized rather than relying on an operator's correct placement of the welding heat, they do not require the same degree of visibility and access to the joint that, for example, manual GTA and PTA welding require. It is difficult to maintain high preheats in GTA welding while allowing both operator access to and sight of the area to be welded (Duval and Doyle 1973).

Research in thick-section EB welding is being done at the Welding Institute in the United Kingdom and in Japan because of the capabilities of the process in that regard. For superalloys, the design and metallurgical factors involved in thick-section EB welds require further study. Superalloys generally require relatively coarse-grained structures for creep resistance at their high operating temperatures, and, for this reason, the fine-grained weld structure of an EB weld might be a disadvantage. The ability to favorably affect grain structure, either during welding or by some post-weld treatment, would represent a significant advance in the application of EB and LB welding technology to superalloys, and therefore should be investigated.

Since the high energy-density processes are likely to be used increasingly, the trade-off between the low heat input and high thermal gradient of these processes should be studied. Improved understanding of this trade-off could minimize some of the adverse effects of the high energy-density processes.

Brazing, Diffusion Welding, and Isothermal Solidification

Brazing is an attractive joining process for superalloys because it does not involve fusion of the components (Kirby and Hanks 1968; Pattee 1973). Diffusion welding is another nonfusion process that relies on careful surface preparation, the possible use of an interlayer material, and the application of pressure to the joint during the heating cycle to produce very high-quality welds that can match superalloy base-metal properties (Crosby et al. 1972; Beltran and Schilling 1976). The isothermal-solidification processes, generally known by the trade names of Transient Liquid Phase (TLP) Processing* (Duval and Owczarski 1974) or Activated Diffusion Bonding** (Hoppin and Berry 1970), are essentially a combination of brazing and diffusion welding. These processes rely on the diffusion of constituents to facilitate joining by locally lowering the melting points of the interface metals. Continued diffusion during isothermal heating raises the melting point to produce welds that match base-metal properties. In both brazing and isothermal-solidification processes, boron often is used to depress the melting point of the joining composition. Moderate amounts of pressure are used with the isothermal-solidification processes. As the components are held at temperature and under pressure, diffusion of the depressant element occurs

*Trademark of Pratt and Whitney Aircraft, Division of United Technologies Corporation).

**Trademark of the General Electric Company.

gradually, raising the melting point of the interface metal above the holding temperature. Thus, solidification occurs at constant temperature. If sufficient time is allowed for the depressant elements to diffuse, it is possible to create a joint that cannot be detected under subsequent metallographic examination. The limiting factors of these processes are that boron can combine with elements such as chromium to form borides rather than diffusing throughout the component in solution at very low concentrations, resulting in a plane of weakness along the joint, and that long times at very high temperatures may be detrimental to some materials.

A problem with brazing of superalloys is that the oxidation resistance and strength of the braze metal may be lower than those of the base metal. Thus, if brazing is used, it may be important to design the assembly so that the braze metal interfaces are not adversely affected.

All of these processes rely on high-quality prejoining cleaning because the tenacious chromium and aluminum oxides formed during high-temperature exposure of superalloy compositions generally interfere with the metal-to-metal wetting necessary to create a satisfactory braze joint. The fluoride-ion cleaning processes that have been developed recently are a significant improvement in cleaning technology for superalloys.

Other Processes

There is a trend to increase the automation of superalloy welding processes. An example is the adaptation of integrated computer-aided manufacturing technology at the Air Force's Air Logistic Centers (ALCs) to improve productivity. An investigation of the effects of automation on superalloy weldability and weld quality is needed since automation may be important in increased productivity and metal conservation.

Several other processes can be considered for superalloy welding applications. The reason that these processes receive less consideration in research and in summaries of the state of the art is that they are inherently specialized (i.e., these processes have one or more characteristics that limit their use to certain specific joint designs and part configurations).

Friction and inertia welding are good examples of this specialization. Relative motion of the two surfaces to be joined creates the heat needed to produce a welded joint, and compressive stresses across the joint deform the molten or heat-softened material to produce a high-quality weld. These processes have been used successfully with superalloys for such applications as the central power shafts of gas turbines (Doyle 1969; Johnson and Kidaines 1973; National Aeronautics and Space Administration 1972). Only a limited effort has been made to extend use of such processes to joint geometries other than circular cross sections.

Similarly, resistance-welding processes have found some specific applications with superalloys. Flash-butt welding is an electrical-resistance process that uses large amounts of current and pressure to produce joints similar to those generated by friction welding, and is commonly used for fabrication of rings. Resistance spot welding, on the other hand, is suited for the joining of sheet components. Flux-shielded processes are not used with superalloys primarily because their nonmetallic inclusion contents and higher gas levels may adversely affect superalloy quality.

GENERAL CONSIDERATIONS

Base Metal

It is difficult to describe the superalloy welding state of technology in broad terms because weldability varies considerably depending on alloy composition and on whether the material is cast or wrought. As mentioned previously, alloys such as alloy 718, low-strength solid-solution alloys, and the cobalt-base alloys are readily weldable. Weldability of the nickel-base superalloys generally decreases as the total content of age-hardening elements (aluminum, titanium, and, to a lesser extent, niobium) increases. There have been many investigations of the joining of the specific precipitation-hardening nickel-based alloys with the most comprehensive summary having been compiled by Prager and Shira (1968). Their review is one of the few attempts to address the weldability of these materials as a class rather than as individual alloys.

Formulas to predict welding response have not been developed for superalloys. Prager and Shira (1968) have related total aluminum and titanium content to nickel alloy weldability (Figure 1). They established a total hardening-element content line above which welding problems are likely to be encountered. Although this is a useful estimate of an alloy's welding behavior, superalloy welding is more complex than the plot indicates (Morochko et al. 1977, 1980). Alloys with considerably higher hardening-element content have been welded successfully and some alloys are more prone to weld cracking than their hardening-element content would suggest. Research in this area might be able to identify additional factors--rate of precipitation, rate of strength recovery on cooling, and others--that would help establish an accurate formula for predicting superalloy weldability.

The optimum heat-treatment for a given superalloy is an important consideration in welding. A number of investigations on this subject have been published, and proprietary practices and patents have been developed to obtain maximum weldability in certain important commercial alloys. Two frequently recommended heat-treatment options are solution treating and overaging. An article by Franklin and Savage (1974) presents a summary of the metallurgical effects and potential benefits of each approach on one alloy. Although a thorough review of current industrial practice with

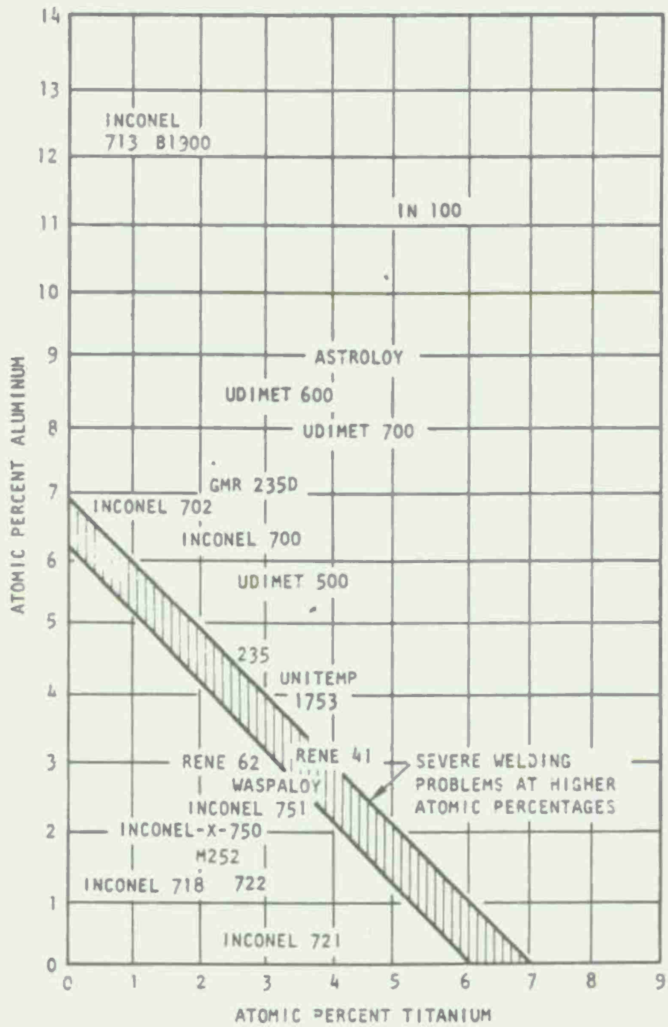

FIGURE 1 Atomic percentage of aluminum and titanium in commercial precipitation-hardenable nickel-base alloys. Maximum service temperature increases with distance from the origin; however, welding is extremely difficult beyond 6 atomic percent total aluminum plus titanium (Prager and Shira 1968).

respect to pre-weld and post-weld heat treatment would be most useful, much of the needed information is likely to be considered proprietary. The patent and technical literature, however, could be useful in summarizing the available information on superalloy heat treatment for optimum weldability.

Minor elements, either intentionally added or present as impurities, have been implicated in superalloy welding problems. The effects of alloy purity on welding are not clear, and a systematic study would greatly improve understanding in this area. This should be approached from the standpoint of maximum tolerable levels of tramp elements as well as minimum content of grain boundary-active elements for satisfactory weldability.

Two types of cracking are associated with superalloy welding. The first is commonly termed microfissuring, hot cracking of the HAZ in the high-temperature region. The second type is called strain-age cracking but also is known as post-weld restraint or stress relief heat-treatment cracking. This type of cracking is concentrated in the high-temperature area of the HAZ and can be more severe than microfissuring. Relatively little research on these two forms of cracking has been reported since 1970. It would be useful to determine the extent of these problems in current service since there are many possible approaches to reducing their occurrence. There would be little point in encouraging further research to understand the mechanism of microfissuring or strain-age cracking in order to develop potential solutions to the problem if the problem does not exist.

The impact of changes in strategic-materials availability on joining should be studied. Particularly relevant is an assessment of whether nickel-base superalloys containing reduced amounts of cobalt are more difficult to weld than alloys containing about 20 percent cobalt. Recent cobalt supply and price disruptions have resulted in aerospace efforts to reduce cobalt usage. If cobalt is shown to have a beneficial effect on weldability, an understanding of the mechanism involved could help establish better welding practices for low-cobalt or cobalt-free alloys.

The effect of ultra-high preheat on superalloy welding also should be investigated. This presents some difficult engineering problems but appears to be an extremely promising approach metallurgically. If sound welds could be made at high temperature (e.g., above the solvus temperature of the second-phase precipitate), subsequent cooling through the precipitation temperature range might be possible without inducing any type of welding defect.

Filler Metals

A promising area for better understanding of superalloy welding is base-metal and filler-metal interactions. Much can be learned regarding the effects of filler-metal properties on superalloy weldability. For example, a recent Air Force contract (King and Anderson 1978) showed that the filler-metal solidus was the only variable that correlated with reduced

HAZ hot cracking in welding of alloy 713C. Filler-metal thermal expansion characteristics and mechanical properties may influence HAZ soundness. Filler-metal strength is likely to affect weldment soundness and hot-cracking tendency. Since a quantitative threshold for HAZ hot cracking in superalloys has not been established, research in this area would be helpful.

Despite widespread use of many nickel-base alloy filler metals, there is no general agreement concerning which filler metal or metals provide the best superalloy weldability and properties. An assessment of filler-metal usage in industry would help to establish the critical factors for optimum weldability of nickel-base superalloys.

Welding superalloys with matching or near-matching filler metals has been hampered by the lack of suitable compositions in fine-diameter wires. Fine-diameter filler metals of matching composition for alloys 713 and IN-738 are now available, however, so that welding these compositions with matching filler metals, should be studied. Even with matching or near-matching filler metals, the strength of a superalloy weld often is lower than that of the base metal. It has been shown that differences in strength across the weld fusion line in superalloys using nonmatching filler metals contribute to low ductility failures in stress-rupture tests of weldments (Jones 1974). This has serious implications with respect to further improving superalloy welding to match the properties of unwelded base-metal. Additional work should be done to investigate the effect of lower weld strength on weld performance.

The following discussions apply to all the materials covered by this report. They are, however, particularly applicable to superalloys.

Pre-Weld Cleaning

As reported earlier under brazing, significant improvements have been made in the cleaning of superalloys. Using this as a base, further investigation and evaluation of these cleaning methods should be conducted for pre-weld cleaning of all materials.

Nondestructive Examination

Improved nondestructive test methods, especially for HAZ cracking, are desirable to improve weld quality. A better understanding of the role of defects and maximum acceptable flaw sizes for the various alloys is needed to establish meaningful nondestructive examination standards.

Communication of Information

Communication of information on welding is hampered by competitive considerations and proprietary interests. When possible, DOD agencies should encourage communication of relevant welding information. Although some avenues for such exchange exist (e.g., the Gas Turbine Panel), additional interchange of welding ideas is needed.

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Chapter 4

THE JOINING OF DISSIMILAR METALS*

The purpose of this chapter is to present a state-of-the-art discussion of the metallurgical aspects of dissimilar-metal welding. Alloys of appreciably different compositions are reviewed, and emphasis is placed on dissimilar-metal joining by arc welding processes. Diffusion welding, explosive welding, brazing, resistance welding, and inertia welding have been used successfully for dissimilar-metal joining but are outside the scope of this chapter.

GENERAL CONSIDERATIONS

Mechanical and Physical Property Differences

Differences in the mechanical properties of two dissimilar base metals of a weldment are important with respect to service conditions (e.g., the weaker member must be suitable for the designed stress). Equally important is the weld filler metal, which may have mechanical properties different from either of the two base metals. Weld dilution can result in additional property variations. Another source of differences in a dissimilar-metal joint is the weld heat-affected zones of the two base metals. Each of these zones should be recognized as potential problem areas for specific service conditions, particularly in cyclic elevated-temperature applications. Despite good understanding of the mechanical properties in these various regions, unexpected performance may result from complex interactions between them. These interactions are difficult to predict analytically, and are therefore a promising area for fundamental research.

When a dissimilar-metal weldment cools, it must accommodate the strain resulting from the thermal-expansion mismatch across the joint. The difference or mismatch in coefficients of thermal expansion (COE) between the materials in a dissimilar-metal joint plays a major role in producing stresses at the joint. This factor is particularly important in welds that operate at elevated temperatures in a cyclic temperature mode.

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*This chapter is adapted from material prepared for the Welding Handbook, 7th ed., vol. 4, American Welding Society, Miami, Florida.

Figure 2 illustrates the linear COE as a function of temperature for the various materials commonly associated with transition joints for steam-plant applications (Goodwin and King 1979). The COE of the ferritic steel is about 30 percent less than that of the austenitic stainless steel. Over the lifetime of a power plant, these joints experience numerous temperature changes due to start-up, operation, and cool-down for maintenance and repair. For a given change in temperature, the stress imposed at the weld is proportional to the differences in COE. Stress analyses of welds between these two dissimilar materials show that their COE mismatch can induce stresses in an order of magnitude greater than those caused by operating pressure and thermal gradients through the pipe weld.

Special consideration should be given to dissimilar-metal joints intended for elevated-temperature service. A favorable situation exists when a joint is maintained at a constant elevated temperature. Stresses then decrease by relaxation that, in turn, lowers the creep rate and the weld reaches equilibrium. In the event of large temperature fluctuations, it is beneficial to reduce the COE effect by using materials with similar expansion coefficients or by using an intermediate material between them that reduces the mismatch of the two adjacent base metals. Similar reasoning can be applied in filler-metal selection. Finally, dissimilar-metal welds should be located in an area of the lowest possible stress.

Microstructural Stability

Large chemical gradients across and adjacent to the interface are possible in dissimilar-metal welds and elevated-temperature service may cause atom diffusion. This movement of atoms over a period of time will alter compositions and produce changes in microstructures and in the mechanical and physical properties of the weld. Dissimilar-metal welds between low-alloy ferritic steel and austenitic stainless steel using an austenitic stainless steel filler metal illustrate this condition. The carbon content of the low-alloy ferritic base metal is generally higher than that of the austenitic weld metal and carbon diffuses from the base metal to the weld. Even where the ferritic material is lower in carbon, the presence of carbide formers such as chromium in the austenitic alloy lowers the chemical activity of carbon and produces a large chemical potential gradient for carbon diffusion from the low-alloy base metal to the weld during post-weld heat treatment or elevated-temperature service. Thus, decarburization and grain growth occur in the HAZ of the ferritic steel with loss in low-temperature mechanical properties. At the same time, the weld metal adjacent to the stainless steel becomes carburized and embrittled and loses corrosion resistance.

Corrosion and Oxidation Resistance

Each dissimilar-metal joint material, including the filler material, has a specific corrosion behavior that must be considered in material selection. Most detrimental corrosion effects arising in dissimilar-metal weldments are due to the formation of galvanic cells that accelerate the

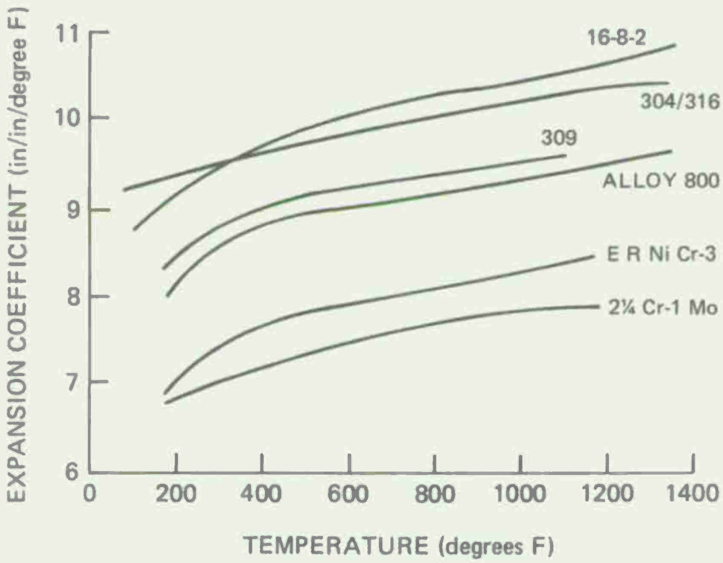

FIGURE 2 Linear thermal expansion coefficients as a function of temperature for various alloys commonly associated with dissimilar metal joints in steam power plants (Goodwin and King 1979).

corrosion rate of the most anodic material. In addition to the dissimilar-metal potential difference across the joint, the weld-metal structure often has different phases that also may set up their own cells and experience galvanic attack at the microstructural level.

The galvanic cell associated with dissimilar metals involving high-strength steels may promote hydrogen embrittlement in the HAZ of the high-strength steel if the steel is the cell cathode. Hydrogen embrittlement may be a problem if the service temperature is in the range of -40 to 200°F (-24 to 93°C) and stresses on the weld are high. Residual welding stress often is sufficiently high to promote hydrogen embrittlement and stress-corrosion behavior. Differences in composition in a dissimilar-metal weldment may cause corrosion problems in addition to galvanic corrosion.

Dilution and the Mixing of Metals

During arc welding, elements from each side of the joint are melted into the weld pool with the filler metal. Solidification results in a new single-or multi-phase alloy. Filler metals used for dissimilar-metal welding should produce ductile welds. The ideal filler metal serves as a solvent to many elements and is diluted by the different base metals without forming a crack-sensitive microstructure. The resulting weld metal also should be stable at service temperatures and at least as strong as the lowest strength parent alloy.

Violent agitation in the weld pool occurs with all arc-welding processes and results in substantially uniform fusion-zone composition with the exception of a narrow band at the extreme edges of the weld bead. This narrow band of melted base metal has been referred to as the unmixed zone (Savage and Szekeres 1967). This unmixed zone usually is wider in dissimilar-metal welds when the filler metal has a higher melting point than the base metal. In multiple-pass welding, the diluted composition of each pass is relatively uniform, but there will be definite compositional differences from bead to bead, especially for those closest to the base metal.

Weld-metal dilution will affect the known thermal-expansion behavior of the filler metal. For example, dilution of pure nickel with copper increases the linear thermal-expansion coefficient. Changes in linear thermal-expansion coefficients can be estimated for the dilution of stainless steel filler material from Figure 3, which uses the Schaeffler diagram axis for effective chromium and nickel (Bennett 1969).

Melting Temperatures

The joining of dissimilar metals by any welding process is dependent on the melting points or ranges of both base-metal alloys. If the melting temperatures are close (within 200°F or 93°C), normal welding techniques and procedures can be applied. When a wide difference in melting temperatures exists, problems are more complex and, in fact, it may be necessary to use brazing, braze welding, or solid-state-welding techniques.

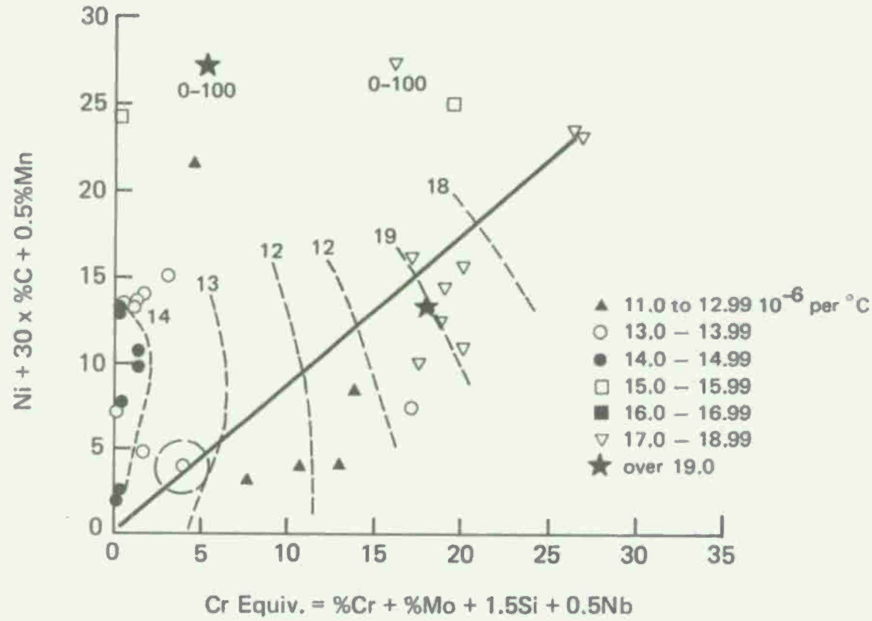

FIGURE 3 Estimated iso-expansion coefficient lines shown using Schaeffler axes (Bennett 1969).

Differences in melting temperatures between the two base metals or between the filler metal and base metal can result in rupture of the material having the lower melting temperature. Solidification and contraction of the material with the higher melting temperature places stress on the lower melting temperature material, which is in a weak, incompletely solidified condition. This problem often can be eliminated by depositing a layer of weld metal of intermediate melting temperature on the higher melting base alloy before the dissimilar joint is welded (buttering). This intermediate layer should serve to reduce the melting-temperature differential. An intermediate layer also is used to minimize thermal-expansion differences.

Thermal Diffusivity

Metals and alloys are good conductors of heat but some are much better than others. The conduction of heat away from the weld pool affects the ability to accumulate sufficient localized heat to melt the filler and parent metals during welding. Welding practice must be adjusted to handle dissimilar metals having greatly differing thermal diffusivities. Often much higher heat input is required and should be directed toward the more heat conductive member of the joint.

It is important to know that the thermal conductivity of an alloy, which influences the thermal-diffusivity coefficient, is a function of temperature as well as alloy content. The thermal conductivity of an alloy that normally has a high heat-transfer rate can be lowered by selectively preheating that side of the joint. This permits greater localization of the welding heat and, thus, a larger penetration and dilution of that alloy.

Preheat and Post-Weld Heat Treatment

Selection of proper thermal treatment, whether it be preheat or post-weld heat treatment, can be a problem with dissimilar joints. The welding of an alloy requiring preheat to an alloy with low energy input requirements can be accomplished provided the preheat can be independently applied to the proper side of the joint. However, post-weld heat treatment after both sides of the joint have been metallurgically united may be more of a problem.

Martensitic stainless steels and some low-alloy steels usually require a heat treatment after welding to ensure weld ductility. Heat treatment of welds between austenitic and ferritic or martensitic steels, however, must be selected so that sensitization of the stainless steel and subsequent loss in corrosion resistance is avoided.

Other Considerations During Welding

Magnetic Differences

Differences in ferromagnetic susceptibility between two alloys can cause arc blow and require the use of special welding procedures to achieve

an acceptable weld-bead morphology and penetration. For instance, in shielded metal arc welding (SMAW) of a nickel-base alloy to a carbon steel, the arc may tend to deflect to the steel side of the joint. This can be corrected by proper electrode manipulation or by using alternating current.

Weld Filler-Metal and Base-Metal Interactions

Filler-metal infiltration into the base metal via HAZ grain boundaries has been reported in certain alloy systems (Matthews and Savage 1971). Usually, the tendency for this to occur is governed by laws of liquid-metal embrittlement. For instance, copper-rich weld filler materials can penetrate carbon steel HAZ grain boundaries since copper and iron are two mutually insoluble elements.

Joint Preparation

Another important variable in welding dissimilar metals is joint preparation. For dissimilar-metal welding, especially in thick materials, use of wider angles in V-butt welds (80 to 90-degree included angles) and smaller root faces to promote as little melting of the parent metals as possible, particularly in the root pass, is often advisable. The wider groove width accommodates more filler metal and less base metal is diluted throughout the joint cross section.

The nature of the specific filler metal also influences joint preparation. This is especially true for dissimilar-metal welding with nickel-base filler materials since molten nickel-base weld metal exhibits low fluidity. Thus, a more open edge preparation will allow better manipulation for proper placement of the filler metal in the joint.

There are exceptions to the concept of using wide-angle grooves in dissimilar-metal welding. For example, it has been reported that for pipe transition joints for boiler service the stress concentrations can be reduced by using a smaller included angle in the edge preparation (Dalcher et al. 1977). This is because a large included angle results in a slender ring of base material coupled to a different material with a different coefficient of thermal expansion. During thermal cycling, large stresses are created at the tip of the thin ring of material. When both the stress state and practical welding procedures are considered for transition pipe joints, joint preparation with 60-degree included angle (30 each) seems to be the proper selection, especially for thinner wall thickness.

BASIC CONSIDERATIONS FOR FILLER-METAL SELECTION

Filler-Metal Requirements

Selection of filler metal is very important in dissimilar-metal welding. The objective in all dissimilar-metal welding operations is to restrict undesirable metallurgical interactions between base metals. It is therefore desirable to select a filler metal that is compatible with both

base metals and that may be deposited and fused with a minimum of dilution. The weld joint should provide a satisfactorily blended gradient from one base metal to the other. Ideally, the filler metal, when properly deposited, should be capable of providing a weld joint that will fulfill many requirements. These are summarized as follows:

1. Defect-Free Welds--The component must be capable of accepting dilution from the base metals involved without forming a crack-sensitive composition or other defects.

2. Structural Stability--The weld metal must remain structurally stable at service temperatures.

3. Physical Properties--The physical properties of the weld metal should be compatible with those of both base metals. Optimal thermal expansion is particularly important to minimize stress concentrations in service. The expansion coefficient of the weld metal should be intermediate between those of the base metals. Equal consideration should be given to thermal and electrical conductivity when they are a design requirement.

4. Mechanical Properties--The weld metal should be at least as strong and ductile as that of one of the base metals at all temperatures encountered in service.

5. Corrosion Properties--The corrosion resistance of the weld metal should be better than that of one of the base metals to avoid preferential attack in the weld joint. This applies to aqueous corrosion as well as to high-temperature corrosion.

Filler-Metal Selection Criteria

Two important steps are recommended in selecting the proper filler metal for dissimilar-metal welding:

1. Determine if the candidate filler metal meets the necessary design criteria such as mechanical properties and corrosion resistance.

2. Determine if the candidate filler metal fulfills the weldability criteria accounting for dilution.

In addition to these steps, two supplementary guides may be of value:

1. A filler metal normally recommended for welding the side of the joint that has the lower melting point should be used. Thus, at least one side of the joint will be fusion-welded with a normally recommended filler metal and the other side of the joint will be braze-welded rather than superheated with a filler material of a higher melting point.

2. A ductile filler metal capable of "forgiving" the strains induced by the welding of dissimilar metals should be used. For instance, nickel-base filler metals are highly ductile and can tolerate considerable

dilution without cracking or developing inferior mechanical properties. Similarly, lower carbon content filler metals are better for dissimilar metal joints. Low-carbon alloys generally are more ductile, more stable, and less prone to hot cracking.

Process Selection Criteria for Dissimilar-Metal Welding

Selecting the right welding process for a given dissimilar-metal joint can be as important as selecting the right filler metal. It should be recognized that different welding processes and techniques offer varying degrees of penetration and dilution of the base metal.

It is not uncommon in arc welding for deposits to be diluted with up to 35 percent of the base metal. The amount of dilution, however, can be controlled by the use of proper techniques. If a combination is being welded in which dilution from one member is less detrimental, the arc should be directed towards that member.

With gas-metal-arc welding, the high-energy spray transfer arc should be avoided. Dilution can be kept to a minimum with techniques using short-circuiting transfer, especially with small-diameter wire.

An outstanding feature of the high energy-density processes is the deep penetration of the weld joints with minimum melting of the base metals. These processes (e.g., laser and electron beam) are specially suited for dissimilar-metal welding.

WELDING CARBON AND LOW-ALLOY STEELS TO STAINLESS AND HIGH-ALLOY STEELS

Austenitic Stainless Steel Filler Metals and the Schaeffler Diagram

Austenitic stainless steel filler metals have been used for a variety of dissimilar-metal welds. The austenitic weld metal dissolves large amounts of interstitial elements, carbon, nitrogen, and hydrogen. Use of austenitic stainless steel filler metal often will prevent underbead cracks in the welding of hardenable steels, although with a loss of strength. Common stainless steel filler metal compositions for welding hardenable steel are 18 Cr/8 Ni (type 308), 25 Cr/12 Ni (type 309), and 25 Cr/20 Ni (type 310).

Weld-metal composition and susceptibility to defects may be predicted by the Schaeffler diagram (Figure 3). It is evident from this diagram that only a small compositional region is immune to welding problems of any type (Bystram 1969). Figure 4 shows compositions susceptible to martensitic cracking below 750^{o}F (400^{o}C), hot cracking above 2280^{o}F (1250^{o}C), brittleness due to sigma-phase formation after heat treatment at 930 to 1650^{o}F (500 to 900^{o}C), and high-temperature brittleness. The remaining small region of preferred microstructure consists of austenitic matrix with 3 to 8 percent residual delta ferrite. It is believed that these pro-

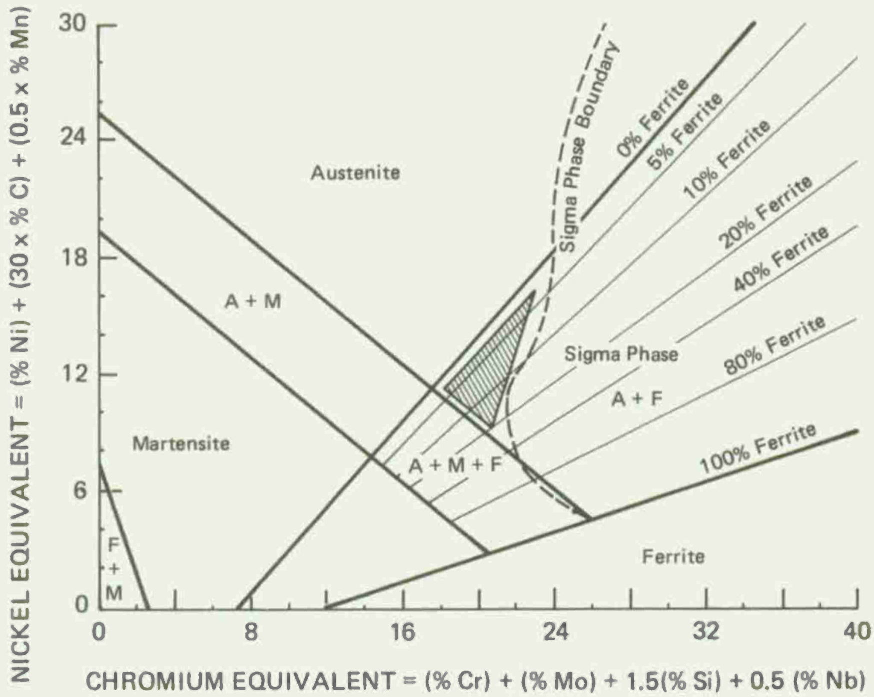

FIGURE 4 Schaeffler diagram showing weld-metal compositions prone to defects or brittleness. (Proposed by C. T. Bystram, BOC-Murex Welding Research and Development Laboratory, England.)

eutectic delta ferrite regions assist in accommodating sulfur and other undesirable elements and, thus, minimize hot cracking of the austenitic matrix. Too much delta ferrite in the weld metal will promote a continuous ferrite phase that can either transform into a brittle sigma phase during high-temperature service or go through the ductile-to-brittle transition during low-temperature exposure.

Selection of the filler metal is the key to making serviceable welds between low-alloy ferritic steels and austenitic stainless steel. When the service temperature is below approximately 700°F (370°C), an austenitic stainless steel filler metal often is used. As indicated by the Schaeffler diagram, weld deposits of austenitic stainless steel filler metals should contain a small amount of ferrite to prevent microfissuring.

For elevated-temperature applications above 700°F (370°C), use of nickel-base alloy filler metals and electrodes (Ni-Cr-Fe alloys) instead of austenitic stainless steels generally is preferred. These alloys offer a number of advantages for transition weld joints in cyclic elevated-temperature service. During welding, they tolerate dilution from a variety of base metals without becoming crack sensitive. The nickel-base alloys have a relatively low carbon solubility, which reduces the carbon migration from the ferritic steel to the weld metal. In addition, these alloys have coefficients of expansion closer to those of the ferritic steels. During thermal cycling, the differential expansion stress, which subjects the joint to thermal fatigue, is located primarily at the interface between the stainless steel and nickel-base alloy-weld-metal. Another possibility for joining ferritic steel to austenitic stainless steel is to provide a third material as a transition piece with a thermal coefficient of expansion between the ferritic and austenitic materials so that stresses imposed at each interface are reduced. This results in a more gradual change in the difference in thermal expansion and thus is helpful in withstanding cyclic thermal stresses. Nickel alloy 800H has been proposed for transition pipe joints between 2-1/4Cr-1Mo steel and austenitic stainless steel used in steam generation service (Jones 1974; King et al. 1977). The design concept for using a graded joint assembly is drawn in Figure 5.

WELDING NICKEL AND COBALT ALLOYS TO FERROUS ALLOYS

Nickel-Base Alloys

Nickel-base alloys can be welded to ferrous materials easily since nickel and iron are mutually soluble elements. Sulphur and phosphorus from steel, however, may cause hot cracking in the nickel-alloy side of the joint. For this reason, excessive dilution should be avoided even though nickel and iron are mutually soluble. Nickel-base filler metals should be used for welding nickel-base alloys to steel.

Cobalt-Base Alloys

Most cobalt-base alloys behave similarly to nickel-base alloys from the standpoint of dissimilar-metal welding. When joining cobalt-base alloys to

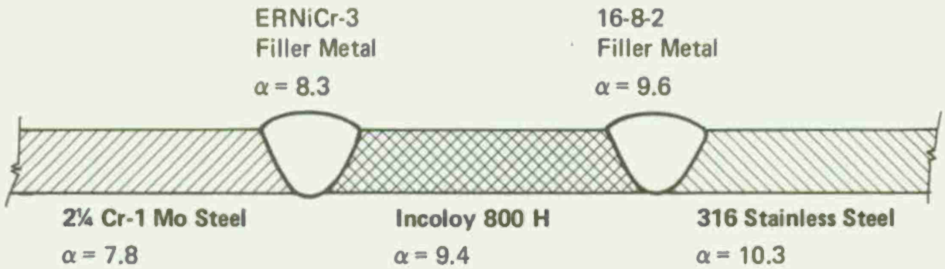

FIGURE 5 Design concept for transition piece between 2-1/4Cr-1Mo steel and type 316 stainless steel subjected to elevated-temperature thermal cycles: mean coefficients of expansion from 70 to 1000°F (21 to 540°C) are noted below each material.

steel, a filler metal matching the composition of the cobalt-base metal generally is recommended, but ductile nickel-base filler metals also may be used.

WELDING ALUMINUM ALLOYS TO FERROUS ALLOYS

From the point of view of welding, iron and aluminum are not compatible metals. Their melting temperatures differ greatly--aluminum 1200°F (660°C) and iron 2797°F (1536°C). In the solid state, aluminum and iron have limited solubility and several brittle intermetallic phases can be formed--$FeAl_2$, Fe_2Al_5, $FeAl_3$. In all fusion-welded joints between aluminum- and iron-base alloys, high residual stresses may be expected because of the difference in the thermal-expansion coefficients, thermal conductivities, and specific heats. The best method of fusion welding these materials is to use a transition piece, thereby allowing more compatible metals to be welded, or to coat one of the two with a third material that is metallurgically compatible with both iron and aluminum. Some limited success has been achieved by using the electron-beam process, which limits the amount of fused metal and, hence, the amount of intermetallic compounds formed (Rayabov et al. 1975).

WELDING ALUMINUM ALLOYS TO NICKEL ALLOYS

Aluminum readily dissolves with nickel in the liquid state but forms brittle intermetallic compounds in the solid state. This greatly limits use of fusion welding for joining these metals. Only limited success has been achieved using barrier layers.

WELDING OF TITANIUM ALLOYS TO FERROUS ALLOYS

Titanium is not compatible with iron. Solid solubility is limited and brittle intermetallic compounds are formed in the solid state causing low ductility welds.

WELDING OF TITANIUM ALLOYS TO NONFERROUS ALLOYS

The fusion welding of titanium to nonferrous alloys generally is plagued by the formation of brittle intermetallic compounds that render the mechanical properties of the weld inadequate.

The joining of titanium to aluminum poses several problems relating to their greatly different melting points and the ease with which these metals form brittle intermetallic compounds--particularly $TiAl_3$. Braze welding using an aluminum alloy filler metal and without melting the titanium produces a minimal quantity of brittle intermetallic compounds at the aluminum and titanium interface, and mechanical properties do not suffer. A similar technique with a different configuration has been used to "braze"

aluminum to titanium by a method involving two separate weld pools (Osokin 1976). Figure 6 illustrates how a GTA weld pool is produced on the titanium (without full penetration) and the heat used to melt the underlying aluminum. The fillet "braze" readily forms if the underside of the joint is protected with inert gas. Good strength, ductility, and integrity were produced for a variety of aluminum alloys with the exception of magnesium-bearing alloys, which showed low bend ductility.

Since columbium (niobium) and titanium are metallurgically compatible, columbium often is used as an intermediate material for joining titanium and nonferrous metals that are less compatible. For example, titanium has been joined to nickel-base alloys using a transition piece or insert of columbium and copper alloy (Gorin 1964). Similar joints made with the EB welding process also proved successful in sheet material (up to 0.080 in. [2 mm]).

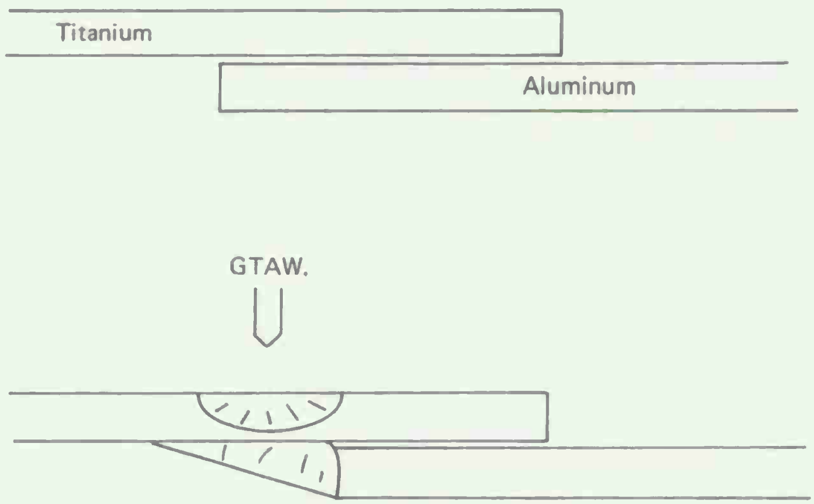

FIGURE 6 Two-weld-pool technique for joining titanium to aluminum.

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Chapter 5

THE JOINING OF CERAMICS

The evaluation of ceramics as structural members in severe environments has increased rapidly due to the need for more efficient energy use and the limited availability of strategic elements for metal alloys for high-temperature environments. In these environments, ceramics must interface with themselves and with metal structures. The Department of Defense has interest in ceramic-to-ceramic and ceramic-to-metal joining for components in heat engines.

This chapter describes the current status of joining ceramics. Ceramics are fundamentally different from metals and, hence, the appropriate joining techniques generally are very different from those reviewed earlier in this report.

BASIC CHARACTERISTICS OF CERAMICS

At room temperature, ceramics are ionic and covalently bonded crystalline solids or glasses (Kingery et al. 1976). They generally are considered as single- or multiple-oxide compounds or glasses. Examples of oxide compounds are alumina (Al_2O_3), beryllia (BeO), mullite ($2SiO_2 3Al_2O_3$), forsterite ($2MgOSiO_2$), barium titanate ($BaTiO_3$), and nickel ferrite ($NiFe_2O_4$). Glasses usually are based on SiO_2, B_2O_3, P_2O_5 (network formers); Al_2O_3 (network intermediates); and Na_2O, CaO, MgO (network modifiers). The common thread, of course, is the use of oxygen as the anion.

Refractory carbides, nitrides, sulfides, silicides, borides, and aluminides have long been considered useful when oxide ceramics are inadequate (Litz 1959, Westbrook 1959). Similarly, glasses based on selenium and sulphur are well established (Doremus 1973) and nitrogen may be substituted for oxygen in silicate glasses (Loehman 1980a). However, with the exception of silicon carbide and tungsten carbide, no nonoxide ceramics or glasses are widely used in industry.

Ceramics have a number of outstanding properties including high-temperature strength, corrosion and oxidation resistance, high electrical resistivity and in some instances thermal conductivities as good as some metals and alloys (e.g., beryllia has the same thermal conductivity as

aluminum and a third that of copper). The one dominant characteristic that has prevented ceramics from competing more successfully with metals is their brittleness. However, at high temperatures some forging is possible (Rice 1970). In spite of their brittle behavior, ceramics currently are being considered for use in heat engines because of the strength and oxidation limitations of metals at high temperature. Several programs that highlight this possible transition are noted below.

STRUCTURAL CERAMICS FOR HEAT ENGINE APPLICATION

Ceramics are now planned to be used in several Department of Energy (DOE) programs. For example, programs for advanced gas turbine (AGT) powertrain development in passenger cars currently are being conducted by General Motors/Detroit Diesel Allison (AGT-100), Ford/AiResearch (AGT-101), and possibly Chrysler (AGT-102).* The engines will be required to operate at 2500°F (1370°C) (U. S. Department of Energy 1980). A second application is for buses (Rockwood 1980; Commerce Business Daily 1981). One of the advantages of ceramics over metals in such applications is that no cooling of the component is required, which simplifies the engine design and increases efficiency. In "ceramic" heat engines, ceramics must be joined both to metals and to themselves.

As early as 1959 carbides were recognized as possible candidates for use in gas turbines (Litz 1959). Titanium carbide appeared to be the most reasonable choice, but like other ceramics, it has poor impact resistance. Borrowing from carbide tool technology, the sintering of a combination of metal and ceramic powders (e.g., TiC plus nickel) was proposed, but this "cermet" combination of metal and ceramic resulted in low impact strengths and the approach essentially was abandoned after 1960, especially as higher-temperature-capability alloys and coatings were developed.

The use of ceramics in gas turbines was reconsidered toward the end of the 1960s when design innovation increased the tolerance for the brittle nature of ceramics. Advances in multi-dimensional finite element analyses provided a new design capability. The thermal and stress environments could be predicted from point to point in a component and, thus, components could be designed within safe limits (Katz 1980).

The Defense Advanced Research Projects Agency (DARPA) concluded that the reliability and credibility of ceramics for heat engine use depend on more accurate life prediction through inexpensive and reliable means of detecting flaws smaller than those currently detected in metals (Burke et al. 1978). The development of nondestructive evaluation techniques subsequently has received much emphasis.

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* Chrysler is not now funded; the two other existing programs have been reduced in scope due to DOE budget reduction.

The candidate ceramic materials for the DARPA Brittle Materials Design Project that began in 1971 were based on the silicon carbide and silicon nitride families. These materials possess relatively good thermal shock resistance at high temperatures due to their low thermal expansion, high strength, and good thermal conductivity. Silicon carbide, for example, has as good a thermal conductivity as beryllia (BeO) at high temperatures (Kingery et al. 1976) but is much stronger and lower in thermal expansion than is beryllia.

During the past decade, significant advances have been made in the use of ceramics in heat engines in the United States and abroad (Bryzik 1980; Katz 1980a, b; Commerce Business Daily 1980, 1981; Rackley 1980; Helms 1980; McLean 1979; Norbye 1981; Richerson 1981a; U. S. Department of Energy 1980).

A recent report by the National Materials Advisory Board (1980), in addition to making numerous specific comments, summarizes the current situation:

> The potential for use of monolithic ceramics in heat engines presents an attractive possibility for significant improvement in engine durability, efficiency and multi-fuel capability...
>
> However, certain problems are involved in using ceramics in engine applications which stem basically from the nonductile nature of these materials. This requires the use of very precise analyses and test techniques to assist the designer in applying ceramic load-bearing components in engines. While some such techniques and methodologies are now available, much more data are required on the reliability of ceramics for these applications. The problems which must be addressed to provide acceptable levels of reliability require further developments in design methodology, quality assurance, and testing procedures for their solution. Perhaps the most crucial problem is that of providing a system to maintain iterative test and development programs which integrate all of the above technology areas and assure effective feedback among them...
>
> Designs suitable for limited-life applications may not be suitable for long-life applications. Of special concern are <u>metal-ceramic</u> and <u>ceramic-ceramic</u> interfaces. Conditions at such interfaces can change with time because of friction, relative motion, oxidation or other effects not observed in the limited time accumulated in tests to date...

> Programs should be initiated to determine design modifications and innovations that may be required for long-life applications of ceramics in heat engines. In particular, the effects at interfaces under typical cyclic engine loading must be evaluated as a function of time.

In an assessment of the DARPA/Navy/Garrett Ceramic Turbine Program, stimulated by failure to meet the 50-hour demonstration goal (Richerson 1981), Rice (1980) concluded that the program was a success in that the major problems with ceramics in heat engines were delineated and rotors were successfully tested. The major problem, he maintained, was contact stresses in the stator structures. Rice outlined a government-funded ceramic heat engine program for consideration as a national goal.

The most recent assessment of the subject (McDermott 1981), however, indicates that federal funding will be drastically cut back after June 1982. This survey indicates that vehicular gas turbine ceramic component engines have no future. The gas turbine engineering community is more optimistic about the future of ceramic components in stationary gas turbines. The assessment concludes that the benefits of developing the ceramic gas turbine are so great that the effort must continue. The survey is more positive about the adiabatic turbo-compound diesel engine and quotes the Cummins Engine Company as being optimistic about the use of zirconia materials in this application.

METALS (FOR JOINING TO CERAMICS)

The metals of interest for heat engines include aluminum alloys, nodular cast-irons, and various grades of stainless steel for diesel engines. For gas turbine applications superalloys are more common. The superalloys are characterized by much higher coefficients of thermal expansion and significantly lower moduli of elasticity than the structural ceramics.

Closely allied to the ceramic research being conducted on gas turbines is that being conducted on heat exchangers. The need for heat exchangers to operate at elevated temperatures and in severely corrosive environments beyond the capabilities of metals is increasing. These range from solar-powered heat exchangers for gas-turbine-powered electrical generation to numerous applications for coal-fired electrical generation and high-temperature industrial heat recuperation. Silicon carbide is the favored material to replace metal in such systems.

JOINING PROCESSES

Rice (1976) has reviewed the development of ceramic-to-ceramic and ceramic-to-metal joining through 1975. He distinguished three basic types of joining techniques:

1. Mechanical joining through the use of mechanical interlocking or mechanical forces.

2. Direct joining by welding, either fusion or solid-state processes.

3. Joining with either organic or nonorganic materials (e.g., adhesives, mortars, cements, or brazing).

The predominant ceramic-to-metal joining technology was developed for sealing oxide ceramics to metals for electron-tube applications, and this technology recently has been extended to sealing devices for high temperature and/or corrosive environment service (Chu 1978; Moorehead et al. 1980; Reed 1966, 1969; Reed et al. 1977, 1979). A vacuum-tight seal generally is required and is achieved most often by metallizing a ceramic member and then brazing it to a metal member as in the refractory metal metallizing process (Reed 1970) or by directly brazing a ceramic member to a metal member with either an "active" metal braze (Canonico et al. 1977; Reed 1970) or with fusible oxides that subsequently may devitrify to a glass-ceramic or stay as a stable glass seal member (Chu 1978, Klomp and Botden 1970; Reed et al. 1979; Simpson 1976; Takamori 1979). The specific refractory metal metallizing process used is dependent on the composition and type of ceramic, i.e., whether it is 94 percent or 99 percent pure alumina body or whether it is primarily composed of BeO (Reed 1965b, 1970). The metallizing point must be tailored to the chemical composition and especially to the glassy grain-boundary phases of the ceramic. Although work to establish the science of the process continues in many countries (Agnivtsev 1968, Klomp 1980, Twentyman and Hancock 1980), the technology generally is considered to be well established and commercial processes produce seals with high yields.

Mechanical and thermal stress analyses of seals were attempted (Mark and Lewin 1965) before finite element analysis techniques were developed; however, the lack of high-temperature data often precluded a thorough analysis. Consequently, experience, standard design configurations (Reed 1970), and iterative prototype hardware are used today to design and finalize joint configurations rather than the finite element analysis techniques cited earlier. Although such techniques obviously should be applied, especially in light of the newer, more demanding stress applications for seals, the lack of high-temperature materials data prevents their implementation.

Seals for high-temperature applications generally have been made for use in vacuum or inert environments. Oxidation-resistant seals that will operate at 1830°F (1000°C) for long times are needed for several emerging applications. Coatings (e.g., the MCrAlY coating) developed for metal turbine blade applications possibly can be used to protect seals that otherwise are suitable for high temperature use.

High temperature heat exchangers are an example of an application that requires a gas tight seal. Recent heat exchanger programs have demonstrated the successful joining of siliconized silicon carbide tubing and manifolds. High strengths have been demonstrated with siliconized silicon carbide joined to itself (Torti et al. 1978). Joints in siliconized silicon carbide tubing also have performed well (Coombs et al. 1979; Metcalf and Napier 1978). However, the lack of technology for joining siliconized silicon carbide to metals has resulted in an increased emphasis on mechanical connectors for these interfaces (Coombs et al. 1979; Metcalf and Napier 1978). In mechanical joining, the ceramic composition is not important. However, if chemical or metallurgical bonds are produced, studies of bond microstructure and ceramic composition need to be initiated.

The requirements for ceramics used for vacuum and gas tight sealing applications are generally different from those for ceramics to be used in heat engines. The prime requirements in heat engines are strength retention at high temperatures and resistance to thermally induced mechanical stresses and to the corrosive environment. Extreme gas-tightness often is not a consideration; therefore, the mechanical joining approach becomes an option to consider.

Discussions with personnel currently working on heat engine programs have indicated that the ceramic-to-metal joining technology now used is largely mechanical since joint movement and compliance are required rather than rigidity. On the other hand, ceramic-to-ceramic joining often is accomplished by solid-state or liquid-state chemical and metallurgical bonding processes.

CERAMIC-TO-CERAMIC JOINTS

Families of silicon nitride and silicon carbide ceramic materials exist (Katz and Lenoe 1980). Silicon nitrides include hot-pressed silicon nitride, sintered silicon nitride, reaction-bonded silicon nitride, the SiAlON's, and chemically vapor deposited silicon nitride. Silicon carbides include hot-pressed silicon carbide, sintered silicon carbide, reaction-sintered or -bonded silicon carbide, siliconized silicon carbide, and chemically vapor deposited silicon carbide.

Typical properties for hot-pressed silicon nitride and silicon carbide are given in Table 2. The coefficients of thermal expansion are lower than those of typical metal alloys used in turbines (e.g., the thermal expansion of silicon nitride is approximately one-third that of the superalloys). Density also is lower (approximately two-fifths that of the superalloys . Modulus of elasticity is higher, particularly for hot-pressed silicon carbide which has a modulus of over twice that of steel. The thermal conductivity of silicon carbide is higher than that of silicon nitride, but both are of the same order of magnitude as the conductivities found in the relatively highly alloyed metals used in gas-turbines. Both types will continue to find applications in heat engines with silicon carbide being favored where high thermal conductivities are required (Ward and Napier 1978), and silicon nitride where lower coefficients of thermal expansion are desirable.

TABLE 2 Typical Properties of Hot-Pressed Silicon Nitride and Silicon Carbide

Property	Si_3N_4 (NC-132)	SiC (NC-203)
Density, g/cm	3.2	3.2
Flexural strength, 4 point Mn/m^2	875	690
Modulus of elasticity, 25^{o}C GN/m^2	317	441
Shear modulus,(G) N/m^2	120	180
Coefficient of thermal expansion per ^{o}C, 20-1000^{o}C	3.2×10^{-6}	4.3×10^{-6}
Thermal conductivity, W/m^2/^{o}C	28	81
Specific heat at 25^{o}C	0.16	0.16

Source: Data from the Norton Company, Worcester, Massachusetts.

The Air Force has begun a program to characterize the most significant materials in each of the SiC and Si_3N_4 families and, through June 1980, evaluated 41 silicon nitride and silicon carbide materials (Larsen 1979; Larsen and Adams 1980). The status of other candidate materials is considered later in this chapter. Continued work on silicon nitride and silicon carbide materials has led to new processing methods, increased strength and oxidation and corrosion resistance, and improvements in other

properties needed for heat engine use (American Ceramic Society 1980; Bourne and Tressler 1980; Schwab and Kotchick 1980; Smith and Quackenbush 1980). The important point to be noted here is that past experience indicates that as the materials to be joined change, so will the processes used to join them.

The joining of reaction-bonded silicon nitride to itself and to hot-pressed material has been the central feature of the DARPA/Army/Ford "Brittle Materials Design/High Temperature Gas Turbine" Program (Baker and Ezis 1978; Goodyear and Ezis 1976). The best joints between reaction-bonded silicon nitride members were made by joining the silicon precursors in an argon atmosphere before nitriding the assembly. The limiting life factor of this joint was its behavior in the corrosive gas turbine environment. Reaction-bonded silicon nitride vanes also were hot-press bonded <u>in situ</u> to a hot-pressed silicon nitride rotor hub. In principle, there appears to be no reason why hot-pressed silicon nitride could not be joined to itself using the same technique. Work is also in progress to bond Si_3N_4 to itself using silicon-alloy brazes (Smeltzer 1981a, b).

Solid-state brazing of silicon nitride has been achieved experimentally but is not considered sufficiently developed for engine use. Filler materials of ZrO_2 powder (Becher and Halen 1978), Al-Al_2O_3-SiO_2 powders (Blair and Milberg 1979; Shinozaki et al. 1980), and Zr foils (Pabst and Elssner 1980) were used. Viscous glass-bonded joints have been used in gas turbine stator assemblies.

Suitable techniques also exist for joining silicon carbide to itself either by hot pressing (Iseki and Arakawa 1980; Rottenbacher and Willman 1980), silicon brazing (Brasell and Tennery 1980; Coombs et al. 1979; Ward and Napier 1978; Ward et al. 1980), silicon-alloy brazing (Smeltzer 1981a, b), germanium brazing (Iseki et al. 1980), or viscous or solidified glass sealing (Brasell and Tennery 1980; Gatti et al. 1979; Metcalfe and Napier 1978; Smeltzer and Metcalfe 1980; Ward and Napier 1978). While silicon nitride and silicon carbide joints using refractory metals as a braze also can be made, their lack of oxidation resistance makes them impractical for use except in low-temperature regions of the engine.

For the establishment of a basic understanding of the metallurgical-chemical joining process, the individual material to be joined needs to be characterized with respect to its joining properties. For example, Loehman (1980b) has produced high-strength joints between sintered silicon nitride bars using an oxynitride glass of the same composition as the grain-boundary glassy phase of the nitride. Joints also were made to hot-pressed and reaction-bonded materials but they were not satisfactory. Adjusting the bonding phase to match the chemistry and microstructure of the material involved may help to overcome these difficulties. The match may be made qualitatively and by iterative experimentation. Calculation of the optimum bonding-phase chemistry from first principles is difficult since little is known about the microstructural properties of silicon nitride. However,

some effort is being made to understand the kinetics of dissolution and precipitation at grain boundaries (Raj 1982) and other microstructural phenomena (Minneat 1982).

Only welding and brazing type joining techniques have been considered here. A discussion of mechanical joints, organic adhesive joints, and nonorganic cement and mortar joints for silicon carbide is given by Brasell et al. (1980). Brasell concludes that mechanical joining, brazing, and solid-state bonding appear to be the most promising methods; however, joining techniques and meaningful proof tests need to be developed for field installations.

The mechanical joining of silicon nitride ceramic components was conducted in the DARPA/Navy/AiResearch program (Richerson et al. 1981a). Unexplained cracking and chipping occurred at interfaces between reaction-bonded silicon nitride stator components. Conventional two-dimensional and three-dimensional finite element analysis indicated that the contact loads were not high enough to cause structural damage; however, further analysis showed that when relative motion occurs in a tangential direction to the normal load, stresses are developed that will cause chipping (Finger 1979; Richerson et al. 1980, 1981b; Richerson 1980). The analysis of the stress levels at the contact area is further complicated by the formation of a silica glass that adds a viscous drag component to the friction between the two surfaces.

Stress analysis has an important role in the development of ceramic-to-ceramic joints, whether mechanically or chemically bonded. The success of the rotor design in the DARPA/Army/Ford program was greatly due to the stress analysis and hardware fabrication sequences (Havstad and Fisher 1978).

With the exception of Loehman's (1980b) work there appears to be little direct government-funded effort aimed at improving the basic technology for bonding silicon nitride and silicon carbide to themselves. However, as indicated, substantial work is being performed as part of large engineering-oriented programs.

Descriptions of various ceramic-to-ceramic bonding techniques are scattered throughout the literature, and no logically structured and consolidated account is available. There also appears to be some duplication of work. A need exists to bring the material together in written report or manual form and to carry out sufficient supplemental work to provide a basic understanding of the joining process. This will permit emerging ceramic materials to be joined with a minimum of problems.

CERAMIC-TO-METAL JOINTS

Ceramic-to-ceramic joints involve materials with similar properties. The converse is true when joining silicon nitride and silicon carbide to metals such as the superalloys. These materials differ greatly in terms of

modulus of elasticity, coefficient of thermal expansion, and thermal diffusivity; therefore, large thermally induced mechanical stresses are set up in joint areas. Although research has been conducted to braze and otherwise firmly join ceramics to the metals (Diem et al. 1980; Hennicke et al. 1980; Pabst and Elssner 1976, 1980; Twentyman 1976), mechanical sliding joints are preferred in practice (i.e., in engine test rigs). In fact, one of the main problems encountered is to prevent bonding of the sliding surfaces (Calvert and Carruthers 1978; Carruthers and Walker 1976; Johansen and Wallace 1976; McLean 1978; Mendelson and McLeod 1981).*

Two classic examples of ceramic-to-metal interface problems are seen in the current DOE automotive gas turbine programs at AiResearch/Ford and Detroit Diesel Allison (Helms 1980; Rackley 1980). The first of these involves rotor attachment. A high-strength monolithic ceramic rotor with a low coefficient of thermal expansion must be attached to a metallic shaft with a much higher coefficient of thermal expansion. The attachment must be very rigid to reduce vibration and maintain the necessary alignments. The joint obviously must be strain-tolerant to survive the thermal cycling during operation and to avoid fatiguing or ratcheting effects after repeated cycling. No solution has been found as yet for this requirement. One approach being taken by AiResearch is to attach the ceramic rotor stub shaft by shrink fitting it into a cavity on the metal shaft. However, there is considerable concern about thermal ratcheting in this design. The second approach is a "curvic" coupling, a mechanical interface approach. This approach was not successful in the earlier Ford automobile gas turbine program due to localized bonding between the hot-pressed silicon nitride and the metallic shaft that led to cracking failures (McLean et al. 1979). A third approach under consideration is the use of a strain-tolerant bond between the ceramic and metal; however, materials had not been selected as of April 1981. A variation of the rotor-bonding problem exists with ceramic turbochargerrotors. The same condition of thermal ratcheting and the requirement for a stiff structure exists. The current approaches are primarily mechanical shrink fitting rather than ceramic-to-metal bonding.

The second area of concern in automotive gas turbines is the mounting location of static ceramic components such as the vanes and shrouds. In this application, mechanical holding is acceptable, but the parts must move in their metal holders and against themselves to accommodate the thermal strains. Thus, the problem is to avoid localized bonding. Possible solutions include the use of surface treatments or of a weak or very-low-modulus interfacial material such as flame-sprayed, low-density coatings. Again, no metallurgical bonding processes exist for obtaining a very compliant bond between the metal and ceramic components.

*It has been reported that metallurgically bonded molybdenum-ceramic engine parts have been manufactured and used successfully in a non-oxidizing environment (Private communication, R. L. Langingham, Lawrence Livermore Laboratory, 1981).

On the DOE AGT-101 program, a radial-flow turbine has been designed by Airesearch to reduce these contact stresses. Detroit Diesel Allison also is expected to use a radial-flow turbine in its AGT-100 program and has designed the engine to minimize damaging contact stresses.

Another example of the requirements for ceramic-to-metal bonding is the adiabatic diesel of the Cummins Engine Company (Bryzik 1980; Kamo 1978). The hot gas path needs to be lined with heat-resistant and low-thermal-conductivity materials to retain the heat in the working fluid. A maximum amount of work must be extracted through the turbocharger and turbo-compounding attachments. A low-conductivity ceramic piston cap is desired. Currently the ceramic caps are attached to the piston by a superalloy bolt, which is expensive and undependable. A thermal-strain-tolerant ceramic-to-metal connection of moderate stiffness is needed. Likewise, the cylinder liners are being held in metal holders by shrink-fitting. Difficulties encountered include the development of tensile stresses after repeated thermal cycling and the loss of compressive loading with increased temperature. Problems also exist concerning the insulation of cylinder heads with ceramics and the insulation of the exhaust passages. In these cases, the ceramic-to-metal joining problem is perhaps less severe in that a more compliant attachment is possible; however, no state-of-the-art methods for bonding the ceramic through an insulating layer to the metal are ready for application in these engines.

Common to all of these application areas is the need to develop a joint that is tolerant of the strains developed during thermal cycling because of the different coefficients of expansion and moduli of elasticity of the ceramics and metals. The problem is not with the development of a localized metallurgical bond of reasonable strength between a ceramic and a metal, but rather with the overall design of an attachment to keep the stresses within acceptable limits. This suggests that analytical and design approaches to joining problems should be conducted concurrently with or before the development of any ceramic-to-metal bond. Some success was achieved with this approach by the British Ceramic Research Association (Twentyman 1978). An excellent treatise on adhesive joints between dissimilar materials (Anderson et al. 1977) as well as a theoretical analysis of a two-material interface (Hein and Erdogan 1971) also are available and provide for better understanding of the analytical approach to joining.

Finite element analysis techniques that have been developed for producing acceptable ceramic structures are being used to minimize stresses in the interfacial joint region. For example, the evaluation of contact stresses in the blade and disk interface was performed on a Gatorized* joint using a NASTRAN** finite element analysis (Mendelson and McLeod 1981). The joint is formed by gatorizing two halves of a superalloy part around the

*A trademark of the Pratt and Whitney Aircraft Division, United Technologies Corporation.

**A registered trademark that refers to the NASA Structural Analysis.

ceramic blade root with or without an intermediate layer. Gatorizing is the isothermal forging of superalloys under superplastic conditions. The interfacial stresses originated from thermal-expansion mismatch and the centrifugal force of the blades against the disk. Blade spin testing showed that failure originated on the dovetail surface at the concave trailing edge as predicted. Norton NC-132 hot-pressed silicon nitride was used.

In all of the mechanically joined ceramic-to-ceramic and ceramic-to-metal component situations reviewed, some form of compliant layer and/or lubricant was inserted between the mating members (Anderson and Bratton 1978; Havsted et al. 1978; McLean et al. 1979; Mendelson and McLeod 1981; Rockwood 1980; Wallace et al. 1978, 1980). In the Detroit Diesel Allison's Ceramic Applications in Turbine Engines (CATE) Program, a cobalt-base alloy (L605) compliant layer is used in conjunction with a diffusion barrier layer of boron nitride on the ceramic turbine blade shank to prevent its bonding to the metal rotor hub (Rockwood 1980). It appears that a study of the effectiveness of these compliant layers and diffusion barriers and also the development of high-temperature lubricants would contribute to the lowering of contact stresses and the prevention of "sticking" between mating surfaces.

Another approach that seems to have merit is the use of compliant felt-metal layers joining solid metal on one side and plasma-sprayed ceramic on the other. Further joining to a solid ceramic can be envisaged. The felt metal provides compliance; rigidity must be provided by additional mechanical means (Erickson et al. 1978). It is important to note that the solid compliant layers operate in the plastic or elastic-plastic region and there are questions concerning fatigue failure with extended service. Felt-metal approaches are easier to constrain to the elastic region but there are questions concerning oxidation with extended life.

A new government-funded program (NAVAIR) directed at joining silicon carbide and silicon nitride to superalloys for service to 2500^{o}F recently was started (Smeltzer 1981 a, b). As far as could be determined, this is the only currently funded government program specifically directed toward advancing the state of ceramic-to-metal sealing for turbine applications. The program is in its beginning stages and it is too early to say whether the joints will be metallurgically or mechanically joined.

EMERGING CERAMIC MATERIALS REQUIRING NEW JOINING TECHNOLOGY CONSIDERATIONS

Only the use of the SiC and Si_3N_4 families of ceramics for heat engines has been reviewed here; however, ceramic composites may also prove to be important (Hillig 1978). Rice (1981) observes:

> The first class of these new ceramic composites are those using fine fibers, e.g., the SiC developed in Japan by pyrolysis of inorganic polymer precursors (primarily polycarbosilanes). Current work conducted at United

Technologies Research Center using glass based matrices has shown promising strength and toughness. Present glass matrice composites are limited to 1830°F (1000°C) which should be sufficient for many important applications in diesel engines. Recent work at the Naval Research Laboratory suggests that these types of composites may not be restricted to the use of glass matrices. Some refractory ceramic matrices may be compatible with the fibers, allowing higher use temperatures. However, much engineering and characterization is needed.

A second and broader class of ceramic composites are particulate composites, i.e., a ceramic matrix containing a dispersion of ceramic particulates. Examples are partially stabilized ZrO_2 (PSZ), and Al_2O_3 with partially or unstabilized ZrO_2. Recent work at NRL has produced Al_2O_3-ZrO_2 composites with room temperature strengths in excess of 100,000 psi, with outstanding thermal shock resistance.

It should be noted that the joining of these materials is as yet unexplored. The fiber composites do suggest the possibility of diffusion bonding, especially in the case where glass based matrices are used. The particulate composites such as Al_2O_3-ZrO_2 may also be amenable to diffusion bonding. Some of these, such as the PSZ and also possibly the Al_2O_3-ZrO_2 may be amenable to fusion welding.

TESTING

The ceramic-to-metal ASTM tensile test is the standard for the electronics industry (ASTM 1964). However, the results are not always consistent with strengths observed in practical devices. Accordingly, many other tests have been devised (e.g., peel tests, modulus of rupture tests, and shear tests) and testing sometimes is carried out on an actual sealed part in order to get a better indication of how the seal will perform in service (Reed 1965a). Service conditions such as a high-temperature alkali metal environment (Hoop 1967) or a cyclic low-high temperature change in an oxidizing environment frequently are simulated (Anderson et al. 1978). Microstructural examinations often are used for both quality control and failure analysis, either on test pieces or parts. Simple nondestructive evaluation (NDE) techniques are used to control the quality of the seal components prior to sealing and to inspect the finished seal. Before metallizing, the ceramic seal area is visually inspected for flaws, chips, pocks, etc. The fired metallized seal is checked for hardness, electrical conductivity, thickness, and surface imperfections and the brazements, for pin holes and good filleting. Brazed seals often are inspected for cracks using dye-penetrant methods and generally are leak-tested to demonstrate a hermetic leak rating of less than 1×10^{-8} atm cc/sec.

The testing of bonded ceramic-to-metal seals for heat engine applications is in its infancy because no such seals have yet been used in heat engines. However, both mechanical ceramic-to-metal joints (Mendelson and McLeod 1981) and ceramic-to-ceramic joints (Finger 1979; Havstad and Fisher 1978) have been tested extensively in engine test rigs, and a fair correlation with the stress-distribution results obtained from finite stress analysis techniques has been obtained (Mendelson and McLeod 1981). In cases where differences exist, a more thorough investigation of the forces existing in the seal area has permitted the analysis to be refined and a better seal to be designed for the next test iteration (Finger 1979). Nondestructive examination of ceramic components has been refined to a high degree for turbine engine ceramics (Heitman 1980) and doubtlessly also will be for seals designed for service in heat engines.

RESEARCH NEEDS

The state of the art concerning the joining of identical ceramics for structural applications appears to be advancing adequately as specific needs arise. The joining of dissimilar ceramics or of ceramics to metals for structural applications is, for all practical purposes, limited to mechanical connections for which methods to minimize localized bonding are needed. The lack of good bonding or nonbonding technology in this field is severely hampering the utilization of ceramics in heat engines and advanced structural applications. The joining of dissimilar ceramics or ceramics to metals is as much a design problem related to acceptable stress generation as a materials science problem and both must be addressed.

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Chapter 6

EMERGING TECHNOLOGIES

HIGH-TEMPERATURE MATERIALS

Several types of high-temperature materials are in various stages of commercial development as alternatives to standard superalloys. Four classes of these materials will be discussed in this chapter: oxide-dispersion-strengthened (ODS) alloys, rapid-solidification-rate (RSR) alloys, directionally solidified eutectics, and single-crystal alloys. Ceramics, although emerging materials, were reviewed in Chapter 5 and will not be discussed further here.

Three mechanically alloyed ODS materials are of interest: Ni-20Cr-0.6Y_2O_3, Ni-15Cr-4W-2Mo-2Ta-4.5Al-2.5Ti-1.1Y_2O_3, and Fe-20Cr-4.5Al-0.5Ti-0.5Y_2O_3. Powder of very-high-solute alloys such as Ni-14.3Mo-7Al-6W-0.04C has been made by the RSR process. Both directionally solidified eutectics, wherein aligned whiskers grow from the eutectic phase within a ductile matrix, and single-crystal alloys are nickel base. The single-crystal alloys are gamma-prime strengthened. The following discussion will apply primarily to the first category because of a higher level of interest in joining these materials.

The physical metallurgy or processing details of these materials will not be discussed, but it is worth noting that they all rely on very specific thermal or thermomechanical processing cycles to produce desired microstructure and corresponding high-temperature properties. Two reasons for discussing these materials are: (1) As usage broadens, applications where joining is needed will increase. The heat engine combustion chamber is an example of an application for emerging materials that requires joining; and (2 Welding is commonly used for repair of manufacturing defects and service damage.

These new material systems are in various stages of development and, except where government contracts or patents are involved, pertinent processing information may be proprietary. Because of the similarities of these systems, however, most of the general observations and assessment of needs for one type of material are relevant to the others as well. Special considerations for individual systems will be noted where appropriate.

JOINING OF EMERGING MATERIALS

It should be pointed out that some of the joining processes discussed here have been known for at least a decade. They are treated here, however, because they are being considered as new approaches for difficult joining conditions.

As is the case for conventional superalloys, other joining processes can be considered for specific product forms. Resistance spot welding has been used to join sheet materials of both the TD Ni-type alloys (Yount 1968; Yount et al. 1967) and MA materials (Franklin 1976). Flash-butt welding of bar stock has been conducted (Yount 1968; Yount et al. 1967), and inertia welding should be considered, especially if dissimilar materials are involved.

Many processes can be considered for joining of emerging materials, particularly ODS and RSR alloys. For example, the descriptive literature for dispersion-strengthened (DS) nickel* lists "riveting, furnace brazing, manual TIG brazing with Hastelloy X** nickel alloy wire, MIG brazing with low carbon NiCr wire and diffusion bonding" as recommended joining methods. The essential factor in selecting a joining process is the level of joint properties that must be attained. With the exception of specific and relatively limited processes such as diffusion welding, it is unreasonable to expect matching or near-matching properties in joints of any of these material classes because of the extreme level of compositional and processing control required to develop those properties in the base metal.

The high-temperature materials considered here are difficult to join; the inherent characteristics of directionally solidified eutectics and single crystals virtually eliminate almost all joining processes. Directionally solidified eutectics are in-situ composites, relying on reinforcing fibers for strengthening; a break in the continuity of these aligned fibers obviously represents a weak point in the structure. For single-crystal alloys, virtually any thermal joining process could lead to the formation of polycrystalline areas with inferior properties. Therefore, feasible processes for joining these two types of high-temperature material may be limited to diffusion welding and brazing. Since development activity with these two material systems is aimed at mechanically attached turbine blade use, there is little reason at this time to encourage joining research on single crystals or directionally solidified eutectics.

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* Sherritt-Gordon Mines, Ltd.

** Trade name, Cabot Corporation.

Most of the research conducted on emerging systems is aimed at meeting specific property targets for particular alloy-joint design combinations. Nevertheless, it should be possible to gain greater understanding of how the joining response of these materials can be improved by studying the basic physical metallurgy and material-process interactions of joining. Although this type of work is difficult to justify because the objective is general, it represents an opportunity to provide significant advances in the technology of joining advanced high-temperature materials.

Traditional welding techniques require high temperatures with possible phase transformations for the melting and solidification necessary to make a joint. Many joining situations make it difficult to use such techniques. Examples are the welding of alloys that experience numerous phase transformations during welding, dissimilar metal joints between materials with great melting point differences, special maintenance welding of joints in very difficult positions and environments, and materials that are fabricated with controlled microstructures. A variety of techniques recently have been applied in these situations, including diffusion welding (Bartle 1975; Mohamed and Washburn 1975; Olson and Liby 1979; Owczarski and Paulonis 1981), silver solid state welding (Grotzky et al. 1976; Knowles and Hazlett 1970; O'Brien et al. 1976; Olson and Liby 1979), and the use of shape-memory alloys.

Processes such as brazing and diffusion welding are particularly appropriate for use with the emerging materials because they require no melting of the base metal. Limitations arise from the need to choose materials and processing cycles that are compatible with the base material; since some emerging material systems rely on thermomechanical processing to develop specific structures for optimum properties, maximum temperatures often exist above which detrimental annealing and/or grain growth of the base metal occur. In addition, compositional changes, (e.g., due to the diffusion of boron and silicon from a brazing alloy) can change the high-temperature properties of the base metal.

Arc Welding

The arc-welding processes are of little use in joining these materials since a significant portion of their strength is derived from carefully controlled microstructure. An arc-fusion-welding operation disrupts this structure, resulting in loss of strength in the weld zone. In ODS alloys, for example, arc welding causes agglomeration of the dispersoid particles that are distributed throughout the base-metal matrix to provide the excellent high-temperature strength as well as a fine grain weld structure as compared to the coarse elongated grain structure of the ODS superalloy.

Arc welding may be considered for these materials when the only requirement is to hold the component or components in a fixed position, or for some other similar low stress requirement. For example, small GTA tack welds could be used to position parts for brazing or other joining processes.

High Energy-Density Processes

The high energy-density processes are of interest in joining the emerging materials because of the rapid heating and cooling of the substrate by these techniques. For example, LB and EB welding have produced properties that are useful for ODS superalloy applications (Kelly 1979 and unpublished research of T. J. Kelly, Inco Research and Development Center, Suffern, New York). Dispersoid retention is much greater with these processes because of the extremely rapid thermal cycle, but solidification with a fine grain structure is still a problem relative to high-temperature creep strength. Joint design (e.g., lap joints versus butt joints) can reduce the effects of this change in grain structure, but it still represents an inherent limitation to the joining of these types of material. The other materials would be similarly affected, although again the extremely rapid thermal cycle might offer some prospects of producing useful joints at least in thin sections. This is an area where further research obviously is needed to define the limits of the process and to lead to advancements in the application of the high energy-density processes to these high-temperature alloys. For example, the possibility of retaining the dispersoid during a laser layer process or distributing the dispersoid in an amorphous layer should be studied.

Diffusion Welding

Diffusion welding usually requires bringing two flat surfaces together under a specific load and holding them for a sufficient length of time to allow diffusion to occur across the joint causing recrystallization, phase changes, and cohesion.

Diffusion welding has been investigated previously for DuPont's ODS alloys TD (thoria dispersed) Ni, and TD NiCr (Moore and Holko 1970; Moore 1970, 1974; and Holko 1973), and eventually a technique was developed that produced matching properties in diffusion welds. Although the TD alloys are no longer produced, this success makes the process attractive for joining Inco's emerging mechanically alloyed (MA) ODS superalloys as well as dispersion-strengthened alloys. Diffusion welding is also an important process for the RSR powder alloys developed by Pratt and Whitney Aircraft and others. It is an essential part of the manufacturing process for the radial wafer blade. Thin RSR alloy laminates prepared by powder metallurgy techniques are diffusion welded into components. The joining and component design require that approximately 2 percent plastic deformation, necessary to achieve the desired weld quality, must be tolerated (private communication with P. Reynolds, Pratt and Whitney Aircraft, Government Products Division, East Hartford, Connecticut).

The use of a specific diffuser also has been found to accelerate the joining process (see Silver Solid-State Joining). Beryllium has been used with nickel alloys and was found to promote rapid diffusion from the diffuser-coated joint into the bare metal resulting in an excessive number of vacancies near the joining interface. The large defect concentration near the interface is believed to promote recrystallization and grain growth allowing cohesion. Further research is needed to provide for a better understanding of the role of diffusers and surface preparation and the selection of the proper thermal cycle.

Silver Solid-State Joining

Silver solid-state joining has many of the same joint preparation concerns as diffusion welding but the process is performed at much lower temperatures and for a shorter time. It involves depositing by electrodeposition, vapor deposition or hollow-cathode-sputtering evaporation techniques, a 0.0002-in. (0.005 mm) layer of silver on each surface to be joined. Silver, which does not form a very stable oxide, ensures clean surfaces.

Silver as an intermediate layer has been used very successfully in achieving high-strength welds at very low joining temperatures. Knowles and Hazlet (1970) first demonstrated this joining technique on silver-coated beryllium using 30,000 psi (210 MPa) joining pressure at 50^{o}F (10^{o}C). O'Brien and co-workers (1976) investigated the influence of welding parameters on weld strength and achieved weld strengths over 100,000 psi (700 MPa) using silver-coated maraging steel tensile specimens.

The application of a thin layer of mercury on top of the silver deposit prior to welding will assist in producing reliable and reproducible high-strength welds. The mercury surface activation does not appear to increase the maximum strength of the silver solid-state welds; rather, it reduces the scatter in the strength values caused by contamination and roughness of the silver coatings. The application of mercury allows storage of silver-coated parts for extended periods of time without reduction in the final weld integrity.

Silver is not the only intermediate metal to be investigated, but it has shown the greatest industrial promise. Further research is necessary to provide a clear understanding of the basic mechanisms involved in welding. With better understanding of the controlling atomic processes, it may be possible to achieve high-strength welds at even lower temperature.

Solid-state welds or brazements that use a thin intermediate layer of a second material may perform mechanically in a similar manner to the base metal for uniaxial loading in the elastic range even though the yield strength of the intermediate metal may be much lower than

that of the base metal. This behavior results from the triaxial stress state generated in the intermediate layer during loading. The weaker intermediate layer is restrained from contracting in the direction normal to the loading direction by the stronger base metal, thus hindering deformation. This triaxial stress state is relaxed by yielding of the base metal, resulting ultimately in failure of the joint. The deformation and fracture characteristics of brazed joints encompassing thin intermediate layers have been treated in detail (Saxton et al. 1971).

Brazing

Brazing of the RSR components also is performed, but it is limited to areas not requiring the full strength and temperature capabilities of the materials (private communication with P. Reynolds, Pratt and Whitney Aircraft, Government Products Division, East Hartford, Connecticut). Brazing of MA 754, a mechanically alloyed Ni-Cr alloy, also is reportedly performed using both proprietary and standard brazing alloys (private communication with M. Lucas, General Electric Company, Aircraft Engine Group, Evandale, Ohio). Although no specific details are available on the current commercial applications of brazing MA 754, that alloy and MA 6000E currently are being studied under an Air Force Materials Laboratory contract (Gerken and Skrocki 1979). Other researchers (Kenyon and Hrubec 1974; Yount 1968; Yount et al. 1967) have examined brazing of dispersion-strengthened alloys. Research should continue in brazing of powder and dispersion strengthened alloys.

Shape-Memory Alloy Joining

Shape-memory alloys, 55-60Ni-40-45Ti, show great promise for the joining of materials at low temperature and in very difficult situations (e.g., in the underwater environment). This joining technique requires that a shape-memory alloy be worked to the configuration that can be put over or around the joint. This initial working must be performed at temperatures below some specific temperature such as 104°F (40°C), and the plastic deformation must not exceed 5 percent. After working, the shape is placed over the joint, and as it warms it returns to its original configuration by way of thermal transformation. The part shape is designed such that on returning to the original form it acts as a high-pressure clamp across the joint. It provides an innovative method for the permanent joining of pipe, tube, and fittings in high-performance piping systems at a reduced installation cost. Aircraft hydraulic systems made of titanium and stainless steel, and underwater pipelines have been repaired using shape-memory alloys.

STRUCTURES

Advanced aircraft power plants are designed for maximum energy efficiency. The rising costs of fuel have made this the primary aircraft engine design goal. A new structural concept in these engines as compared to older engines is the integral or drum rotor design wherein the rotors are welded together rather than mechanically tied (Figure 7). The advantages of this design are increased rotor strength and stiffness, reduced weight, improved stability, and lower cost, all of which contribute to better energy efficiency. The selection of a joining process for the drum rotor is, of course, vital. Rotor materials generally are titanium alloys and superalloys. Because of the need to join relatively thick sections without filler metal, the high energy-density processes, in particular the electron beam process, are of interest.

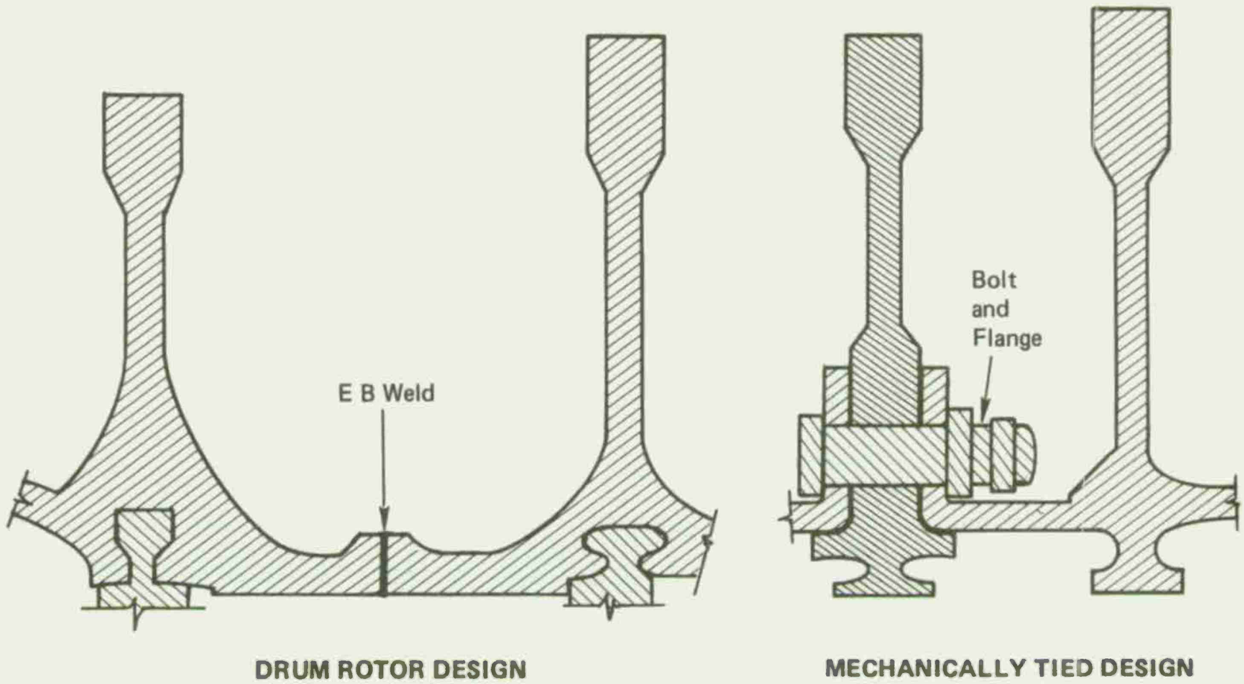

FIGURE 7 Comparison of drum rotor and mechanically tied rotor designs.

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This report presents a review of the science of joining and the state of technology for joining similar and dissimilar metals to one another, ceramics to ceramics, and metals to ceramics. With respect to ceramics, mechanical joints and metallurgical bonds are considered. Important emerging technologies and advanced joining techniques are discussed, and some of the critical gaps in fundamental joining knowledge that limit progress are identified. Future research is recommended to form a basis for improved understanding of the

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joining process in all its many forms, and to develop new and improved joining methods to meet future design challenges. The metal-to-metal combinations will continue to be the major joining assembly concern of the Department of Defense as it is in the industry.

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